AN ANALYSIS OF THE RELATIONSHIP
BETWEEN A PASSIVE MICROWAVE SENSOR
DATA SET AND SOIL MOISTURE CONTENT

THESIS

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Preface

The purpose of this thesis was to analyze a set of passive microwave sensor values and identify if a relationship to the ground soil moisture existed. Determining soil moisture through remote sensing has the potential to influence certain aspects of the tactical environment. Through identification and quantification of the other variables that affect the microwave response, this potential can be realized.

The weighting technique developed in this thesis may become a useful tool in reducing the variance of sensor readings. This technique can be useful with both active and passive remote sensing. Continued investigation with other data sets is necessary to determine its true value.

I would like to thank a number of people for their support in producing this work. First, I would have been without even the basis for this thesis without the help of Dr. Ike McKim and the rest of his research group at CRREL. I wish to thank Helene Wilson, who not only performed the original analysis of the data, but also spent a great deal of time answering my most rudimentary questions about the research. Additionally, I would like to thank my advisor, Lt Col Robinson, and my reader, MAJ Kelso, for providing me with both the inspiration to get the job done and the ideas to make it happen. Finally, I thank my wife Gloria for running the rest of the show while I tamed the lions in the center ring.

Robert J. Vasta

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Abstract

The purpose of this thesis was to analyze a collection of passive microwave sensor output and determine if a relationship existed between that output and soil moisture content. It was also the objective of this thesis to identify procedural errors which may have hindered the thorough analysis of the data set and propose potential solutions.

In processing the data into a form which could be analyzed, a weighting technique was developed to help reduce the variability in the sensor readings caused by the large footprint size. This weighting technique used a Bessel function to represent the decrease in beam strength within a footprint. Multiple footprints containing the same sample ground location were then weighted based on the ground sample position in the footprint.

The study failed to show that any relationship exists between soil moisture and passive microwave response. The results, rather than being significant, are inconclusive. Many procedural and processing errors in the experiment, coupled with a lack of data on some important variables, left the analysis with only a small chance of success. However, these errors are identified and potential solutions for many of these errors are identified.

The weighting technique showed a statistically insignificant increase in the relationship values, yet with additional study could prove to be an asset in this field.

AN ANALYSIS OF THE RELATIONSHIP BETWEEN A PASSIVE MICROWAVE SENSOR DATA SET AND SOIL MOISTURE CONTENT

I. Introduction

General Issue

A wide variety of satellite sensor information is processed and made available to users throughout the world. The information is collected from both commercial and military satellites around the clock. The U.S. Department of Defense uses this information, through each of the military services, on a daily basis. Although many uses exist, from weather information to identification of an aircraft carrier's exact position, new uses are continually being developed.

The Army, for example, is searching for ways to incorporate satellite information into the tactical scenario. In other words, in what ways can the commander in battle use satellite data to help create an advantage for his unit? One potential area is the use of satellite information to determine engineering properties of specific ground locations. Useful information includes soil type, soil moisture content, and vegetation type. Significant amounts of research have been done in the areas of vegetation type and soil type. However, there has been almost no research done investigating the use of satellite data to identify soil moisture content (11).

Remote sensing, by satellite or other means, can be either active or passive. As will be explained shortly, the active method is the only feasible way of providing the necessary information from space. However, analysis of passive remote sensing information, collected at low altitude by aircraft, can be helpful in determining the utility of active remote sensing by satellite.

The United States Army Corps of Engineers, in its combat role, has a mission requirement to provide mobility support on the battlefield. Two methods of support are the construction of expedient airfields or airstrips and the set-up and operation of water obstacle crossing sites when normal crossing methods like bridges are unavailable. In choosing locations for these types of mobility support, several characteristics of the areas are important. One physical characteristic important in the engineering evaluation of potential sites is the bearing capacity or strength of the soil. Soil strength must exist at levels high enough to support the potential loads from landing aircraft or armored vehicles. How, then, does soil moisture fit into the problem?

There is significant utility in knowing the moisture content of soil. The percentage of moisture in the soil and strength of soil are directly related. In addition, soil type and soil strength are also directly related. These three factors are critical to an engineering evaluation of a potential location. Generally, as the moisture increases in soil, the strength, or bearing capacity, decreases.

The microwave portion of the electromagnetic spectrum can be effective in identifying moisture content of soil, much more so than the current commercial visible and infrared sensors (9:488,505,526). Both visible and infrared light is stopped by the soil, while microwave light can penetrate to (active) or emit from (passive) the level of interest. In order to successfully use microwave data the size of the pixel (the smallest segment of a satellite or aerial photo) must be no larger than the area of interest on the ground. That is, if the area of interest is ten meters wide, then the pixel must be smaller on a side than ten meters. With a larger pixel, one would be uncertain whether the information was accurate for the area of interest. The pixel size, then, defines the resolution of the image. Active remote sensing has resolution that is many times better than passive remote sensing at high altitudes. For this reason, satellite remote sensing of soil moisture should be performed with active sensing.

Of course, the most critical aspect is to evaluate collected data and show that a relationship does exist between soil moisture content and the response of the microwave sensor. Previous research has indicated a strong correlation between both passive and active microwave response and soil moisture. Further experimentation in both areas will aid in the complete understanding of the subject. At the request of the Army Cold Regions Research and Engineering Laboratory, this researcher reevaluated a data set of passive microwave response with the intent of extending current knowledge in the field.

The Objective

It is the objective of this thesis effort to analyze a data set collected using a passive microwave radiometer to identify whether a strong and distinct relationship can be shown to exist between the sensor information and ground truth measurements taken of the actual moisture content. A by-product of this analysis will be a review of the experimental process used in obtaining and processing the data set and a discussion of any changes in experimental procedure potentially useful for future experimentation. Finally, it is the purpose of this thesis to briefly analyze current literature and explain why active satellite sensors are necessary for the identification of soil moisture in a tactical scenario.

Theory

The purpose of this review is to provide the reader with an understanding of current technology and how it impacts on this thesis effort. Several key topics will be addressed. These topics are soils, the relationship between soil strength and soil moisture, remote sensing, the use of microwave sensing to detect soil moisture, and factors which affect the ability to detect microwave soil moisture reflectance and emission. The discussion of factors will be covered as subtopics of the microwave feasibility topic. In addition, this review will include a short discussion of the need for active microwave sensors in satellites to determine soil moisture.

Soils

Soils are divided into different classes based on their physical characteristics. There are four types of soils: gravel, sand, silt, and clay. These types are further delineated as either coarse-grained or fine-grained. Gravel and sand are coarse-grained, while silt and clay are fine-grained soils. Organic material is included in the fine-grained soils. Organic soils are important because they are generally the weakest of soils. Presence of organic soil in a soil mixture will cause it to be weaker than the same mix without organic material. Normally, soil types are mixed in their natural state. An additional identifier is the gradation of a soil. A well-graded soil is one that has a good distribution of particle sizes, while a poorly graded soil has either a uniform distribution of particles or a gap in the distribution of particle sizes. The gradation of soil is important because this characteristic affects how well a soil holds water (14:4-7).

The Relationship Between Soil Strength and Soil Moisture. Soil strength is a function of many of the characteristics of soils previously mentioned. However, there is a close correlation between the soil moisture and the soil strength. For engineering efforts, it is extremely important to know the moisture content of the soil at the work site. There exists an optimum moisture content for each soil type at which the strength of the soil reaches its peak value. This range is generally between five percent and twenty-five percent moisture. Above and below the optimum moisture level, the soil strength drops dramatically (14:15-16). This information is graphically portrayed in Figure 1. This soil strength is called bearing capacity and is measured in the military using a test called the California Bearing Ratio (CBR). "This test is a measure of the bearing capacity of a soil based upon its shearing resistance under carefully controlled density and moisture conditions" (2:2-4 to 2-5). This test is the method by which military engineers determine where and how to build load bearing structures such as runways and fording sites.

Remote Sensing

"Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact

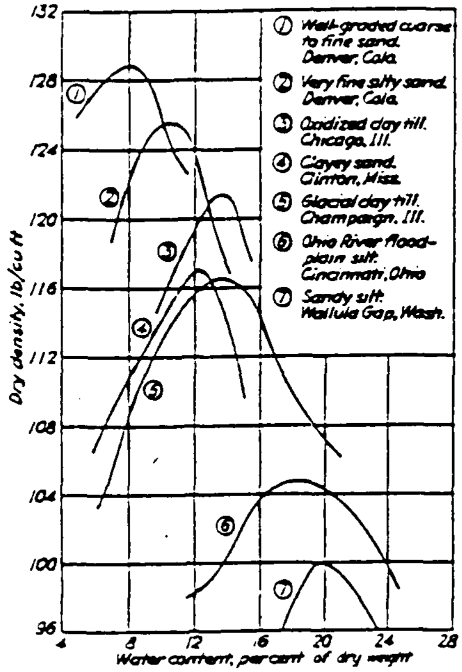

Figure 1. Moisture-Density Relations for Various Soils Showing Maximum Strength Levels (14:16)

with the object" (9:1). As mentioned previously, most remote sensing information is obtained by collecting light reflected from or emitted by the target. Light, however, does not exist only in the visible region that human eyes see. Visible light is just a small portion of the entire spectrum, existing with a wavelength of between .4 and .7 micrometers. When light interacts with an object, a combination of three things will happen: absorption, transmittance, and reflectance. The reflected light is what is seen and what gives an object its color or tone. For example, if an object reflects a large amount of green light, that object is seen as green. In the entire spectrum of light each object reflects, absorbs, or transmits light based on the wavelength of that light. These levels of interaction are constant for each type of object. Because of this fact, a person is able to distinguish that a stop sign is red every time he looks at it. Each object has a spectral reflectance curve associated with it. The curve changes only when the object changes. This knowledge is useful in object identification. In order to distinguish one object from another, a wavelength of light is chosen that reflects differently from each. Then, sensors gather information on the amount of light reflected from each at that wavelength. Next, a determination is made from the data. Most often this sensing is done from aircraft, but in the last decade space satellite sensors have begun to perform this same task. The sensing (airplane or satellite) can be active or passive. Passive sensing uses reflected light emitted by any other source than the sensing unit or light emitted by the target itself. Active sensing uses reflected light that is shone on the target by the sensing unit (9).

The Use of Microwave Remote Sensing to Detect Soil Moisture

The microwave portion of the light spectrum is between 0.5 mm and 1 m in wavelength. Microwaves are a good choice for sensing information about the surface of the earth for several reasons. One significant problem with sensing information from and above the atmosphere is the atmosphere itself. The constituents of the atmosphere, particularly water and carbon dioxide, absorb many wavelengths of light. Light in the microwave region transmits through the atmosphere very well. This is equally true for passive and active microwave sensing.

Passive Microwave Sensing. In a passive system, the radiometer receives signal power in two ways, emitted and reflected. This discussion will explain how each is dealt with.

Emission. Every object emits light as a natural function of its temperature. Theoretically, it is assumed that all bodies are totally absorbent and are called black-body sources. The radiation emitted by these sources is described by the Planck Function. For each temperature a black-body curve exists that can be plotted as the Planck Function vs. wavelength. The Planck Function values are given in units of power per unit area per unit wavelength interval. A graphical view of Planck Function curves for several different temperatures is shown in Figure 2. The Stefan-Boltzmann Law is an expression which describes the total power per unit area radiated by a body at all wavelengths. This value is the area under the Planck Function curve and is expressed as:

$$B(T) = \sigma * T^4 \qquad (1)$$

where

$B(T)$ = power emitted per unit area
σ = a constant, 5.67×10^{-8} $(W/m^2)*K^{-4}$
T = temperature (Kelvin)

At a temperature of 293 K, approximately room temperature, the value of the power per unit area is 4.18×10^2 W/m^2.

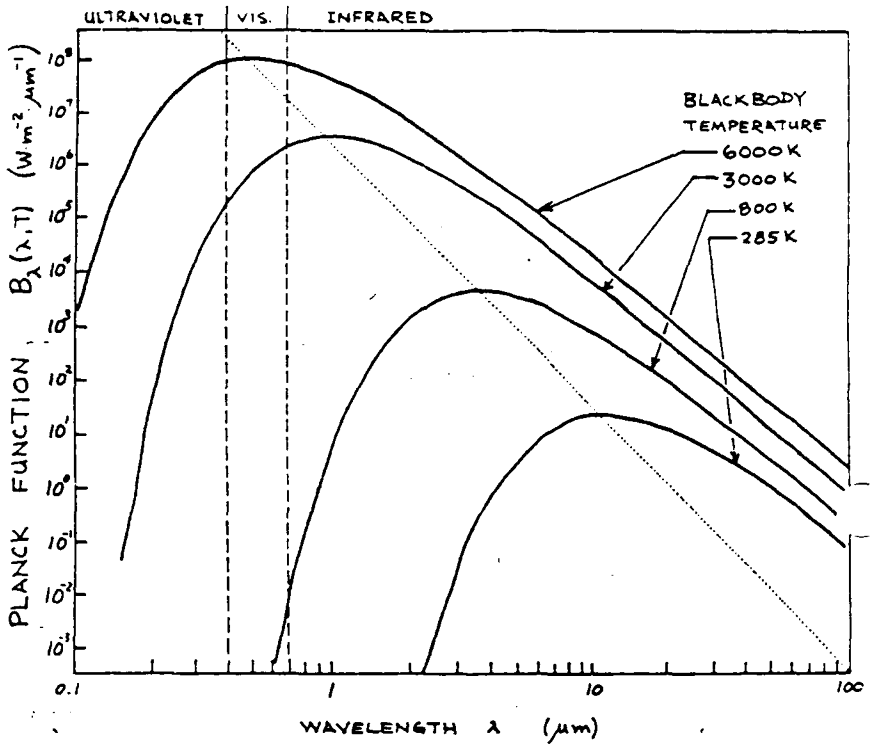

Figure 2. Planck Function vs. Wavelength (5:16)

However, the interest is in the microwave emission at this temperature. In order to determine that value, the Rayleigh-Jeans limit is used, which is an approximation of the long wavelength values on the Planck Function curve. This is expressed as:

$$B(T,\lambda) = 2\pi c k_B T/\lambda^4 \qquad (2)$$

where

$B(T,\lambda)$ = power emitted per unit per wavelength interval
c = 3.0×10^8 m/sec
k_B = 1.38×10^{-23} J/K
λ = wavelength (meters)

By assuming that there is a linear portion of the black-body curve, evaluating the equation at the two limits of the microwave spectrum, averaging those two values and multiplying by the wavelength interval, the power per unit area is found to equal 60.92 W/m^2. This value is only fifteen percent of the total power. The majority of this value is at the short wavelength portion of the microwave spectrum. The sensor used in this thesis effort has a bandwidth of 25 MHz from 21.045 cm to 21.406 cm (10:17). The power from this portion of the spectrum comes to only 1.356×10^{-9} W/m^2, a considerably smaller value.

Emissivity itself is a measure of what portion of the light is emitted. Each object has some portion emitted, some portion reflected and some portion transmitted. It is assumed that the value of transmitted light is negligible for soil. So, the value of emissivity and reflectance together equal 1. For the soil, the emissivity is fairly high, with a value of at least 0.75 and as high as 0.90. This means that the reflectance has a value of from 0.10 to 0.25.

<u>Reflection</u>. The sun is the only source of microwave radiation that could affect the sensor in reflection from the ground. However, the amount of microwave light that is emitted from the sun is small. Just as with the soil, the sky is treated as if it were a black-body for evaluation purposes. So, with a temperature

of about 15 K, the value of emitted microwave sunlight is 15/293 = .05 times the amount of emitted microwave light from the soil. The reflectance of the soil is only about 0.15. Thus, the value of the reflected microwave light is only about (.15/.85) * 0.05 = .009 times the value of the emitted light. This value is considered negligible (4:1276-1277; 5:13-15).

Active Microwave Sensing. Active microwave sensing provides increased resolution over that of passive microwave sensing. Synthetic aperture radar allows us to make use of the coherent nature of light to get extremely high resolutions. An active system makes use of the backscattering from a target. The radar sends a signal to the target and then receives a return of the signal called backscatter (16:973). The backscattering is dependent on many different variables which will be discussed further in this chapter. However, the strength of the microwave signal sent by the radar instrument and reflected by the target is much stronger than that of the soil microwave emission. Thus, this emission does not interfere with the sensing procedure (9:7).

Variables Affecting Sensing

Several ground factors affect the sensing process of soil moisture. Kiefer reports "some of the factors affecting soil reflectance are moisture content, soil texture (proportion of sand, silt, and clay), surface roughness, the presence of iron oxide, and organic matter content" (9:19). This discussion will not include the consideration of iron oxide or organic matter content. Both of these are actually part of the soil texture area and do not need separate discussions. Other factors include vegetation (18:490; 20:825), moisture ratio as a function of depth (17:18), and the dielectric constant difference between water and soil (15:12).

Soil Texture. Soil texture is the breakdown of a soil into percentages of four groups: sand, clay, silt, and organics. These percentages affect the soils ability to hold water and its ability to drain effectively. Contrary to Keifer's assessment, more recent investigations have shown mixed results in this area that is obviously not well understood. As reported by Dobson, several studies have shown no correlation between the two. In particular, a study done by Dobson and Ulaby in 1981 and reported by Dobson examined three separate soil types having distinctive soil textures and found a linear relationship that was independent of soil texture (3:27). These results were contradicted by Wang in two other experiments. He found that soil texture did have an affect on the response signal when testing two different soil textures (20:831) and again using three separate soil textures. His results showed that for both active and passive systems, soil texture was a factor (20:50).

Soil Roughness. Soil roughness is a measure of the irregularity of a soil. This roughness affects the reflectivity of the soil. Increased roughness decreases the reflectivity and, therefore, increases the emissivity. Thus, roughness can have a significant affect on both active and passive sensing systems (16:972-973). Schmugge, Wang, Shutko, and Dobson all reported on the affects of soil roughness on soil moisture reflectivity. Schmugge reports that soil roughness adds noise into the sensed data. Noise, in this sense, is unwanted signal (light) that interferes with the signal from the soil moisture. "The presence of variations in surface cover conditions such as roughness . . greatly reduces microwave sensitivity to soil moisture and introduces scatter" (15:17). As experimentally shown by Choudhury and reported by Schmugge, the relationship between rough surfaces, smooth surfaces, and reflectivity could be expressed by:

$$R = R_o \exp\ (-h \cos^2 \phi) \tag{3}$$

where R is the reflectivity, R_o is the smooth surface reflectivity, and h is a parameter related to height variations of the soil surface (15:17). This relation was developed for passive microwave sensing. Other experimentation found that the roughness effect only began when the difference in soil height was in the neighborhood of one centimeter or greater (17:22). Both of these reports indicated that the angle of observation was also critical in roughness considerations, with reflectance increasing as the incidence angle became smaller. This observation was verified by Wang in another experiment, again involving passive systems. However, this experiment failed to show a good correlation between the calculated values of soil moisture and active system backscatter (20:832). Wang's experiment was important because he tested both active and passive systems together, attempting to gain information about the relationship. All too infrequently have experiments been done with both systems, so almost no comparative data is available.

Vegetation. Vegetation is perhaps the most important factor which influences the microwave signature of soil moisture. Vegetation causes a loss of accuracy in the relationship between measured sensor values (both active and passive) and soil moisture. The cause of the difficulty is linked to both the reflectivity and absorption of the vegetation exhibited by many types of plants. As the soil microwave signal heads toward the sensor, it is attenuated by the vegetation as it passes through. Additionally, the vegetation sends out a signal of its own, which acts as a large source of noise. Corn, for example, is so bright (high absorption) that it completely eliminated several data points from consideration in the preliminary report on the data set under investigation in this thesis (22:6-7). In an experiment by Theis, multispectral imaging to support microwave sensing of soil moisture was clearly shown to be a necessity. Using the multispectral imaging to identify crop and other vegetation types and then removing the vegetation noise effectively allowed for the evaluation of soil moisture. The thermal brightness values were normalized using the vegetative information (18:492-495). Wang found that when both active and passive systems are compared, vegetation affects on reflectivity are more pronounced for the passive reflectance. Additionally, he reports that vegetation was much less a problem at small view angles (20:832). A zero degree view angle means that the sensor is looking straight down onto the surface. It is logical that viewing the surface at a very small angle would help to eliminate absorption by plants because a smaller angle means a smaller distance from the sensor to the target. The smaller distance in turn means that the amount of vegetation seen by the sensor is also less. The absorption of the vegetation is identified by its optical depth as:

$$t = (at)\sec(\tau) \qquad (4)$$

where τ is the optical depth, t is the canopy thickness, and a is the volume absorption coefficient, which depends on the dielectric coefficient of the vegetation (15:14-15). For corn, this optical depth effectively reduces the signal of the soil moisture below a useful sensitivity level (15:15).

Moisture Ratio as a Function of Depth. When soil moisture is not uniformly distributed in the top 10 cm of the soil, a correction must be applied to the values of reflected microwave data. This correction is based on the reflectivity of each of the distinct levels of moisture, the thickness of these levels, and the specific wavelength used in the sensing (17:18).

Soil and Water Dielectric Constant Difference. The dielectric constant of a substance is a ratio of capacitance with and without the substance present. That is, it is a ratio between the ability to pass charge through the substance in consideration versus the ability to pass charge through a void. All substances decrease the ability to pass charge (electrical current) (1:450). Dielectric considerations are related to the vegetation problems encountered in microwave study of soil moisture. Several studies have shown that because of the significant difference between the dielectric constant of water, approximately 70, and that of soil, approximately 3, useful information, such as soil moisture can be calculated. However, that same difference causes vegetation to be a problem. As vegetation is mainly water, the reflectance problems mentioned before can be better understood. The sensors must attempt to distinguish between the reflectance of the water in the vegetation and the water in the soil in active systems. In passive systems, the noise created by the emission of microwave light by vegetation, overpowers that of the soil moisture. In the case of corn, the amount of water in the plant is at least as great as is in the soil (15:12-20; 19:54-58).

Active Microwave Sensing from Satellites

The key word in explaining this topic is resolution. In order to allow the use of satellite remote sensing in the tactical environment, particularly identification of soil moisture, the proper resolution must be achieved. For the tactical situations outlined previously the required resolution can be no worse than 25 meters. That means that the pixel size can be no larger than 25 meters on a side. Why is resolution of this type required? In order to properly plan the required work effort and to identify the best location, soil moisture information in an area no larger than the construction site must be available. A river crossing site, either bridging or rafting, will normally be no larger than 50 meters wide. For an airstrip or airfield, the width of the strip can vary according to the aircraft, but again 50 meters is a good estimate of the required information. A final controlling feature is the propensity for soil moisture to vary from location to location. Soil moisture can vary drastically within a 5 meter radius, although soil moisture tends to follow the soil patterns with much less variation. So, how can we achieve this required resolution from space?

Passive Remote Sensing from Space. For passive remote sensing, the minimum resolvable angle between two point sources is defined by the following equation: $\phi = 1.22\ \lambda/D$, where λ is the wavelength in meters and D is the diameter of the antenna (6:157). The largest antenna diameter that is currently scheduled to go into space is 2.4 meters (6:158). So, with the wavelength of 21.4 cm used in soil moisture determination, the maximum resolution angle is .109 degrees. At a low orbit of 200 km, the spatial resolution on the ground would be approximately 380 meters. This is obviously unusable. Until extremely large antennae are put in space, or until phased array antennae are developed to be constructed in space, passive remote sensing for soil moisture is not a possibility.

Active Remote Sensing from Space. For an active microwave sensor, the most effective means of getting high resolution is the use of focused synthetic aperture radar (SAR). For SAR the resolution is defined by D/2. For a diameter of 5 meters, the resolution can be as good as 2.5 meters. As an example, the shuttle SAR has a resolution of about 25 meters. Obviously, this is the technique to use, as the resolution is just what is needed for the tactical scenario (6:193).

Summary

In the evaluation of soil moisture using microwave sensing, either active or passive, it is evident that many factors must be considered and accounted for in experimental data. The amount of vegetation is a significant problem to contend with, as is soil roughness. Utilizing the known difference between dielectric constants, however, allows the researcher to more accurately assess data. Adjusting the angle of view, or look angle, is also an important consideration for both soil roughness and vegetation. Finally, soil texture has been shown to be a factor in soil moisture identification. Considerable experimentation has been performed to help quantify these factors. Within this analysis, attention will focus on these variables, within the limits of the data set.

II. The Data Set

The data set that will be analyzed in this thesis effort was collected in the Kanawha watershed in Hancock County, Iowa during the morning and afternoon of 19 August, 1987. It was initially evaluated by Wilson, who presented a preliminary analysis in June, 1988. This chapter is a rough summary of the information presented in Wilson's report. What follows in this chapter is an explanation of each variable on which data was collected and the equipment and methods used in collecting and evaluating the data. The experimental effort was set up and funded by both the United States Army Cold Regions and Research Engineering Laboratory (CRREL) located in Hanover, New Hampshire and the Goddard Space Flight Center, Institute for Space Studies, a part of the National Aeronautics and Space Administration (NASA), located in New York City, New York. The ground truth measurements were collected by members of the Agronomy Department of the Iowa State University. This effort was not a dedicated experiment, however. While performing overflights at another site, some flight time became available. The researchers used this time to send the aircraft to the Kanawha watershed. The conditions for the overflight were not exceptional. The day was overcast and a light rain fell through a portion of the flight time, particularly during the final two flight lines.

Sampling Locations

To support a study of the relationship between microwave emission and soil moisture content, two groups of data were collected. The first group was collected as ground truth and consisted of gravimetric soil moisture, land use, soil type, elevation, bulk density, and soil texture. The second group was collected during an aerial overflight performed at the same time as the ground sampling. This set included the microwave readings, soil temperature readings, and a color video of the overflight. All of these elements were time coded to allow for linking of information. The ground truth information was collected at eighty-eight specific locations within the watershed. The technique used to select the locations was a stratified systematic unaligned sampling process. This process ensures a random sampling of the area in question while also ensuring that all sections of the area are sampled. Additionally, this technique ensures appropriate representation of certain key variables in the sampling set. In this case, the watershed was broken down into eighty-eight equal areas. Each area had a random sample chosen from within its boundaries. The variables of soil type, land use, and elevation were each proportionally represented in the sampling set as well (12). However, this sampling technique led to some problems in the data set that will be discussed in detail in Chapter 5.

The locations, once chosen, were plotted onto a 1:24,000 USGS map and sent from CRREL to the Agronomy Department at the University of Iowa. These locations were then transferred to a 1:15,840 soils survey map. Graduate students actually performed the sampling. They were directed to the sampling site locations by field notes (Appendix A) written by Fenton. These notes were based on agricultural sections - mile square areas which are bordered by the road network of the Iowa farmland. North-south and east-west directions in feet were given from the corners of the sections, which in all cases corresponded to road intersections. The sections themselves are numbered and are annotated on both USGS and soils maps of the area. This method of physically locating the points on the ground introduced an error which will be discussed in the conclusions section of this document. Of the eighty-eight points chosen for sampling, three were not sampled because of poor ground conditions and two of the locations were moved for the same reason. Once the ground sampling was completed, a corrected copy of the sampling locations was sent back to CRREL and this information was used to link the sensor readings with the ground truth values.

Ground Truth Variables

As was described earlier in this chapter, several ground truth variables were recorded for each sampling location. Of these variables, only the soil moisture had the potential to vary with time at each location. The other variables were constant with regard to the location.

Soil Moisture. The soil moisture was sampled at two depths at each location: 0-5 centimeters and 5-10 centimeters. The sampling was done using the gravimetric technique and identified soil moisture as a percent of water by weight. At each location, two samples were taken, corresponding to the two depths of interest. Each of these samples was then weighed, providing the sample weight. The samples were then oven-dried at 110 degrees Celsius for 24 hours, which is the standard procedure in this process. The samples were again weighed and the value of water weight, W_w was then calculated by subtraction, $W_{Sample} - W_s$, where W_s is the weight of the oven dried solid matter. The gravimetric soil moisture (GSM) content is then defined as $w(\%) = 100*W_w/W_s$ (7; 13:11).

Soil Type. The sampling points were plotted onto a soils survey map to identify the predominant soil type at each location. In some cases, only one soil type was in the area. However, in over half the sampling locations, two or more soil types were present. In the original analysis, no more than two soil types were considered for any sampling location. This is a possible source of error in the analysis. The soil types are identified by a classification number or soil mapping unit (SMU), assigned by the local or national soils survey organization.

Land Use. Land use was identified for each sampling location by crop type or other use, such as a road or bare field. However, for the original analysis, the land use was identified using a land cover classification map based on the July 17, 1987 SPOT image of the area. The average normalized difference vegetation index value for the SPOT pixels was classified into specific land cover for each of the sampling locations. This method uses levels of greyness to identify patterns and groupings of vegetation, which are then classified based on index values (22:3).

Elevation. Although the elevation was identified for each of the sampling locations, this variable was not used in the analysis of the data set.

Bulk Density. The bulk density of the soil is a measurement of a soil's dry unit weight or dry density, measured in this case in grams per cubic centimeter. It is used to convert a gravimetric soil moisture value to a volumetric value of soil moisture. The average bulk density for a soil is catalogued by soil type (Appendix B). Although bulk density is catalogued, variations exist within soils. This variable can be calculated from field sampling to give the most accurate assessment possible. In this study, however, average values were used.

Soil Texture. Soil texture, or the percentages of sand and clay in a particular soil type is also catalogued (Appendix B). Soil texture is used to convert volumetric soil moisture into field capacity percentage of soil moisture. Sand is defined as a mineral grain, ranging in size from 0.003 inches to less than 0.25 inches (2:1-2). The percentage of sand is important because the greater the quantity of sand in a soil, the more likely the soil will drain well. In this analysis, the amount of sand affects the capacity of the soil to hold water. Clay is defined as particles that are smaller than 0.0002 inches and display an adhesive characteristic known as plasticity. Clays absorb water slowly but retain that water tenaciously. The amount of clay in a soil type also effects that soil's capacity to hold water (2:1-2 to 1-3).

The Overflight

As readings were being taken on the ground, measurements were also being taken from the air. A Pushbroom Microwave Radiometer (PBMR) was flown over the designated watershed in a NASA C-130 aircraft. In its explanatory report of the PBMR, NASA describes a radiometer and its function as:

> A radiometer is a receiver designed to measure the noise power emitted by an object. The level of this received signal is extremely small and is in fact generally smaller than the noise level generated within the receiver (10:2).

To overcome the noise of the receiver, a filtering and amplification process helps to eliminate the problem. A more complete description of the radiometer is in Appendix C. The PBMR is a 4-beam, horizontally-polarized instrument which operates at 1.413-GHz or a wavelength of about 21 centimeters. As shown in Figure 3 the antenna receives signals in four beams.

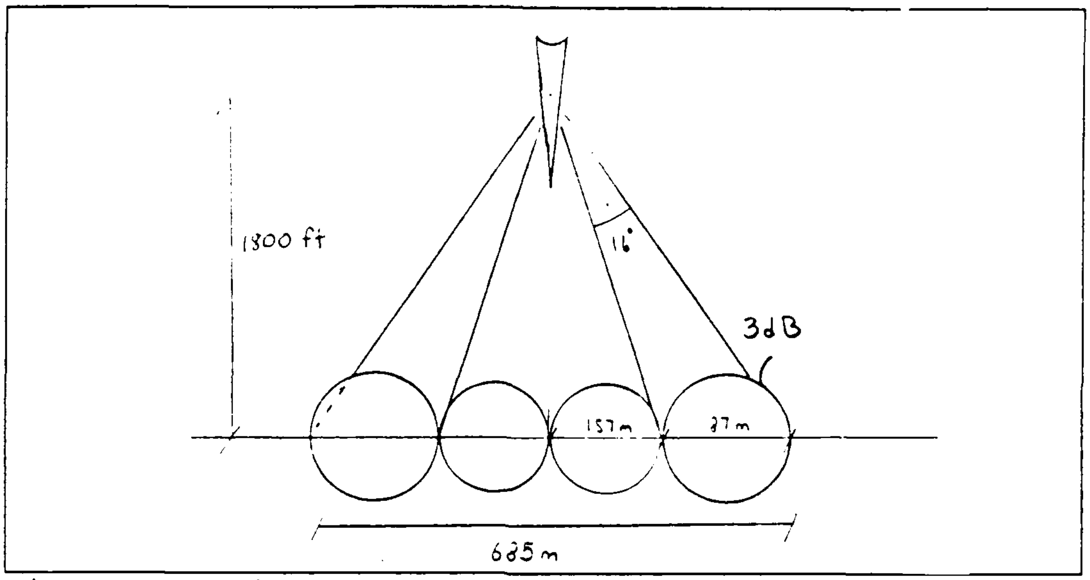

Figure 3. Aircraft Mounted 4-beam Microwave Radiometer Beam Pattern

The near-nadir beams are centered at 8 degrees to either side of the perpendicular and the far beams are centered at 24 degrees to either side of the perpendicular. The readings are recorded for each of the four beams every half second. The cones shown are the 3-dB bands for each signal. Because of the height of the aircraft, the two outer beams "see" a cone with diameter approximately 20 meters wider than the inner beams. The entire width for the four beams is 685 meters. The resolution in the cross-track direction is equal to the diameter of the given beam. The aircraft traveled at a speed of about 170 miles per hour and so, with a reading being taken every half second, traveled between 38 and 42 meters each second. During the overflight, wind caused a variation in velocity, resulting in an increased velocity in the north-to-south flight lines. As each beam footprint or pixel is wider than 42 meters, except for the extreme edges, more than one footprint was taken for most of the sampling sites. As was mentioned, eighty-eight sites were chosen initially to be sampled. However, three were not sampled and another twenty-six were not captured in the overflight. Through some error in plotting the flight lines, about one third of the watershed was missed. The flight lines went alternately north-to-south and south-to-north. An overlap of about 15% existed to each side of the flight line as flight line centers were about 530 meters apart and flight lines were about 685 meters wide. This overlap allowed for several sampling points to be part of two adjacent flight lines.

Brightness Temperatures. As was explained above, four readings were taken every half second by the radiometer's four beams. Each of these beam readings was a value of noise power or brightness temperature which corresponds to the emission of microwave radiation at the wavelength of interest. Brightness temperature is related to the emissivity of the soil by the equation T_B = emissivity*T_S, where T_S is the temperature of the soil (8:1138). The soil temperature was also identified by the PBMR equipment.

Soil Temperature. Besides the four brightness temperature readings taken each half second, a soil temperature reading was taken each half second. This reading, the PRT5 thermal infrared soil temperature, was used in establishing the emissivity of the samples during the analysis phase. The temperature value was recorded in degrees Celsius and converted to degrees Kelvin. Therefore, the emissivity = $T_B/(PRT5 + 273.15)$.

Color Video. A nadir view color video was taken beneath the aircraft. This video was time coded to allow a matching of this flight information to the readout from the PBMR. The field-of-view of the video closely matched the cross-track of the microwave sensor.

Data Compilation

The key element in linking the airborne values to the ground truth values lay in the identification of which beam went with which ground location. In processing the data to complete this task, Wilson made several assumptions regarding the data set. These assumptions were:

1. The footprint of the beam was a rectangle measuring approximately 540 feet in the cross-track direction and 130 feet in the direction of flight (23).

2. The beam chosen was the one with the sample location most centered.

3. Any footprint in which more than two soils were present was reduced to the two major soils present.

4. Bulk density values were averaged between the soils present based on the approximate area ratio between them.

5. Soil texture was also averaged between the soils present based on the approximate area ratio between them.

The Linking of Sample Site to Beam. After plotting all the sample sites onto a 1:24,000 USGS map, Wilson addressed the question of which beam went with which site. Utilizing the color video, she carefully located the frame of the tape that corresponded to the location of the sampling point. To locate the correct frame, she used identifiable ground locations such as roads, intersections, creeks, houses, and fence lines to match ground location on the video with that of the map. After recording the time of the particular frame, Wilson then matched that to the PBMR readings, also identified by time on the readout. A lag of about one second was identified during the tape viewing between the video time and the PBMR time. This was accounted for in choosing the correct scan line. Once the correct scan line was identified, it was simply a matter of measuring from the aircraft centerline, identified on the videotape with crosshairs, to the sample point. This allowed easy identification of the correct beam from the identified scan line.

Soils. To ensure that the soil information was accurate, Wilson mapped the chosen beam onto a soils survey map. This allowed her to easily identify the soils within the beam footprint. With this information she calculated bulk densities and soil texture values as described above.

Volumetric Soil Moisture Percentage. In addition to gravimetric soil moisture (GSM), two other types of evaluation exist. One of these, volumetric soil moisture (VSM) is the amount of water by percent volume in a soil sample. This value is calculated by utilizing the gravimetric soil moisture and the bulk density (BD) of the soil. Numerically, %VSM = %GSM * BD.

Field Capacity Moisture Content. The field capacity (FC) of a soil is also expressed as a percentage. It is defined as the quantity of water retained in the soil divided by the soil's moisture capacity. Numerically, %FC = %VSM/(0.30 - .0023 * %Sand + .005 * %Clay) (18:491). Notice how this equation accurately takes into account the moisture characteristics of both sand and clay as described earlier.

Beam Angle. In addition to the variables previously mentioned, Wilson also identified the beam angle as a variable. Based on which beam was used from a scan line, they were broken into two groups - near-nadir and off-nadir. Beam angle has been shown to have an affect on the sensor response because of the change in the size of the vegetative layer and the change in reflectivity based on the soil roughness. This distinction was used in her analysis of the data set.

Data Analysis

The preliminary analysis of the data set was performed using graphical and statistical methods. The analysis revealed a limited, if not nonexistent, relationship between the soil moisture values and the thermal brightness microwave readings of the PBMR. Scatter plots were developed between each combination of the dependent variable, either thermal brightness or emissivity, and the independent variables of gravimetric soil moisture, volumetric soil moisture, field capacity, or the PRT5 values. These plots indicated no strong relationship between the variables. This indication was verified through linear regression analysis (Table 1), producing product-moment correlation coefficients no greater than 0.08 for the data set as a whole. A breakdown of the data into sub-groups of near-nadir and off-nadir footprints showed an R^2 improvement to 0.28 for field capacity/near-nadir footprints. Another sub-grouping of known soils, without outliers or footprints which included roads had a value as high as 0.32. In addition to the regression analysis, the investigator performed difference-of-means t-tests and Kruskal-Wallis Analysis of Variance with ranks tests on the brightness temperature variables. These results are summarized in Appendix D.

Table 1. Product-Moment Correlation Coefficients for Microwave Observations vs. Moisture Measurements

Microwave Variable	Number of Observations	Gravimetric Moisture %	Volumetric Moisture %	Field Capacity %
TB	All sites	0.04	-0.06	0.05
Emiss	N = 58	0.08	0.01	0.08
TB	Near-nadir	-0.12	-0.26	-0.28
Emiss	N = 29	-0.11	-0.25	-0.27
TB	Far-nadir,	-0.10	-0.16	-0.13
Emiss	less outliers #15 & #71 N = 27	-0.08	-0.17	-0.15
TB	Known soils,	-0.09	-0.22	-0.17
Emiss	less outliers #19, #20, #71 N = 38	-0.09	-0.22	-0.16
TB	Same as above,	-0.15	-0.26	-0.32
Emiss	less roads N = 26	-0.12	-0.24	-0.28

The investigator's intent was to identify those variables that had a significant impact on the brightness temperature values. These results showed no great link between the variables and sub-groupings with a few exceptions. Bulk density of the soil appeared to have a slight significance on brightness temperature as did the sub-groupings of soil association when both corn and road footprints were removed. These variables will be investigated in this thesis effort as well. Finally, the investigator evaluated the variations in gravimetric soil moisture, considering surface characteristics, using the same tests (Table 2). This portion of the analysis yielded no significant information, as the expected increase in gravimetric soil moisture was seen in the clay type soils. This evaluation did, however, verify that the gravimetric measurements taken during the data collection were not erroneous, at least in comparison to the soil type.

Table 2. Variations in Percent Gravimetric Soil Moisture with Surface Characteristics

Variable	N	Mean	St. Dev.	Range	Test Statistic
Land Cover (SPOT)					
Beans	20	31.5	3.71	24.45-38.11	
Corn	11	32.1	5.75	25.69-43.67	H = 0.1
Unclassified	5	31.0	4.61	25.73-39.45	
Soil (Homogeneous Texture)					
Loam SMU's	10	28.28	2.65	24.45-31.77	t = 1.86
Clay Loam SMU's	17	32.04	5.79	18.30-44.33	.08 level

Summary

Wilson concluded that establishing a relationship between the in situ data and the PBMR microwave data was made impossible because of three major problems. First, inaccuracies in the in situ data was noted. This problem was two-fold. Uncertainty in the accuracy of the designated sample locations was one part. Uncertainty in the representativeness of these in situ measurements to the soil moisture in the entire footprint area was the other. The second major problem was the nearly uniform moisture state of the Kanawha watershed when the observations were made, leading to difficulty in producing a significant regression curve. The final major problem was the high concentration of vegetation in the watershed. This high quantity of vegetation can overpower the soil moisture signal. This effect was evidenced by the variation of the brightness temperature mean values with and without corn, a high moisture plant.

III. Methodology

This chapter describes the methodology used to collect the data and process that data for the analysis that follows. Additionally, this chapter explains the analysis techniques that will be used in the next chapter. The collection of the data is similar in many ways to the procedures used by Wilson. However, in several key areas, the procedures and processing techniques used in the preparation of this thesis were quite different from those used previously. These differences will be explained in detail in this chapter. Those techniques that were similar will also be briefly discussed. A compilation of all data points and their associated variables are listed in Appendices E and F.

Sampling Locations

In order to ensure that the sample locations were as accurate as possible, a copy of the original field notes was requested from Dr. Fenton, University of Iowa Agronomy Department (Appendix A). From the original field notes, the locations were plotted on both the USGS 1:24,000 map and the Hancock County, Iowa soils map. This procedure was different from that used in the earlier analysis. In the earlier analysis, a map showing the plotted locations was sent to CRREL from Iowa. An overlay was created and then digitized. The digitized locations were then redisplayed onto another overlay, which was then utilized by the investigator. This procedure was used because the emphasis of the first investigation was on producing a digitized image for the entire watershed, using the thermal brightness values as the levels of greyness. The analysis of the data set for the specific sampling locations was a secondary aspect of the research. By using the original field notes, any plotting errors inherent in the Iowa map or in the transfer of the locations were eliminated. Also, through a number of telephone conversations with Aaron Steinwand, a graduate student who worked on the project, locational errors were identified for three sampling points. These locational errors were not accounted for in the earlier analysis. Correcting these errors was important in linking the correct footprint(s) to the sample locations.

Ground Truth Variables

Ground truth variable information was collected by the Iowa personnel. In some cases, verification was performed in conjunction with this thesis to validate these values.

Soil Moisture. The gravimetric soil moisture values were utilized as collected by the Iowa personnel. There were no procedural differences between the original analysis and this effort.

Land Use. While at the sampling locations, the Iowa personnel identified the land use for the sites. This analysis utilized the identified land use values. This procedure differs from the original analysis in that the original analysis used a SPOT image classification from the month of July, 1987 to assign land use values. To verify these values, the sample locations were identified on the color video. A few locations were then identified as having a different land use than was reported by the Iowa sampling crew.

Bulk Density. There was no difference in the process used to identify the bulk density of different soil types.

Soil Texture. There was no difference in the process used to identify the soil texture for the different soil types.

The Overflight

The information collected during the overflight by the PBMR was utilized in exactly the same way in this research as in the previous analysis.

Data Compilation

In replotting the locations of the sampling points, a cursory evaluation of beam choices for the sample site to footprint link showed several differences. Upon further evaluation, more than 90% of the sample points were linked to footprints different than used by Wilson in her analysis. As was mentioned in the previous chapter, the key element in processing the data is the correct linking of the footprint to the sample site.

Just as was done in the previous analysis, this researcher used the videotape to link locations and times. To achieve this link, utilization of identifiable map features was necessary. In spatially locating these identified map features, a large amount of judgment was necessary. For this analysis, distances were measured on the video monitor using a ruler and then were converted to map distances using an appropriate scaling factor. The scaling factor was determined by using the town of Kanawha as a grid reference and measuring the distances between streets. Although the scaling factor was established with a fairly high degree of accuracy, the human ability to measure accurately is certainly an error that is inherent in this analysis. However, the size of the error is less than 10 meters at any location because the measuring instrument was accurate to 0.125 inches which corresponds to about six meters on the video monitor. This error is only a factor in the identification of the non-road based flight lines and their associated sample locations. Of the six flight lines that covered the watershed area, two were tracked over roads, making the identification of the other four the problem. Once the flight lines were established, the time of overflight was established for each location. This was done by using the velocity of the aircraft and the crossing times of the road network. The time was established for each road crossing, with an accuracy of better than 0.1

seconds. This was possible because the videotape had a constant number of frames per second, thirty-one. Thus, the time was established as "x seconds and x frames". Using the equation velocity = distance/time, the aircraft velocity was established for each one mile segment of the flight lines. It was assumed that the flight speed was constant through the range of each segment. Once the airspeed was established, the time associated with each sample site was recorded using the same equation. In this case, of course, the velocity and distance were the known values.

Having established both the flight line and the sample location, it became a matter of identifying which footprint(s) actually included the sample location in question. The following method was applied to identify these footprints:

1. The time that the aircraft was directly overhead of the sample point was identified as shown above.

2. A one second lag was added to the aircraft time to allow for the difference between the aircraft time and the computer time. This lag was identified utilizing the audio portion of the color video. After each flight line was completed, the researcher on board the aircraft gave the vital statistics for the flight line, including the aircraft time and the computer time. A one second difference was constant throughout the overflight.

3. The closest sensor footprint time was then identified from the computer output.

4. The difference in time was then established, and, using the known aircraft speed for the particular flight line, the north-south distance offset was established. This offset was the distance the sample point was from the east-west centerline of the footprint.

5. The sample point distance from the flight line was then determined in the east-west direction. Based on the established flight line, a map measurement revealed this distance.

6. The east-west distance was then compared to the width of the footprints to determine which footprint of the four contained the sample point.

7. Using the known beam diameter, and the east-west offset, the north-south beam chord length was established. That is, the width of the chosen beam in the north-south direction was established using the equation for a right triangle, $x^2 + y^2 = z^2$. In this case, x is the east-west offset, y is 1/2 the length of the chord, and z is the beam radius.

8. Using the known flight speed of the aircraft and the identified times that sensor readings were taken, all other footprints which included the sample point were identified. For example, if the chord was 150 meters in length, the velocity of the aircraft was 80 meters/second,

and the time between samples was .5 seconds, then the sample point would fall into at least three footprints and perhaps four, depending on the actual times used. Figure 4 shows this procedure displayed graphically.

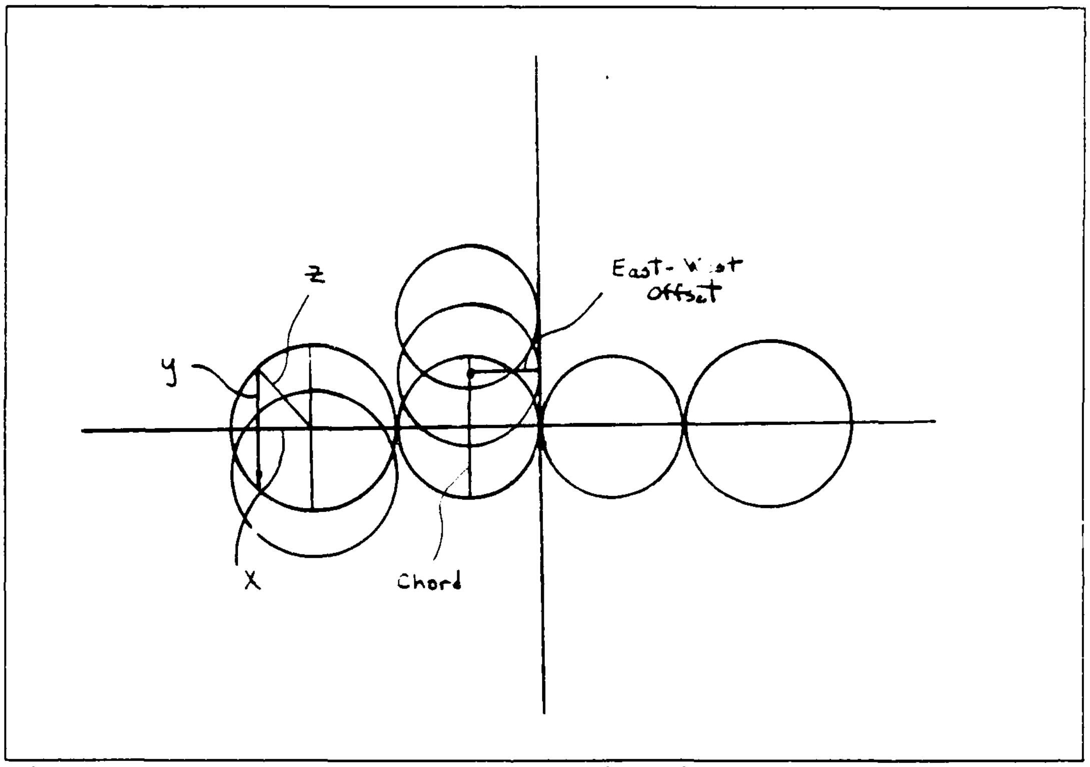

Figure 4. Footprint Identification for Sample Site Locations

The results for all 58 sample points are included in Appendix E. Notice that a considerable number of sample points are included in two flight lines and are within as many as nine footprints.

Soils. To ensure that the soil information was accurate, considering the numerous changes in site locations, a scaled beam template was created and used with the soils map. Once the beam location was established in the previous section, the template was used to identify, albeit crudely, the fractions of soils present in the footprint. This procedure is shown graphically below in Figure 5.

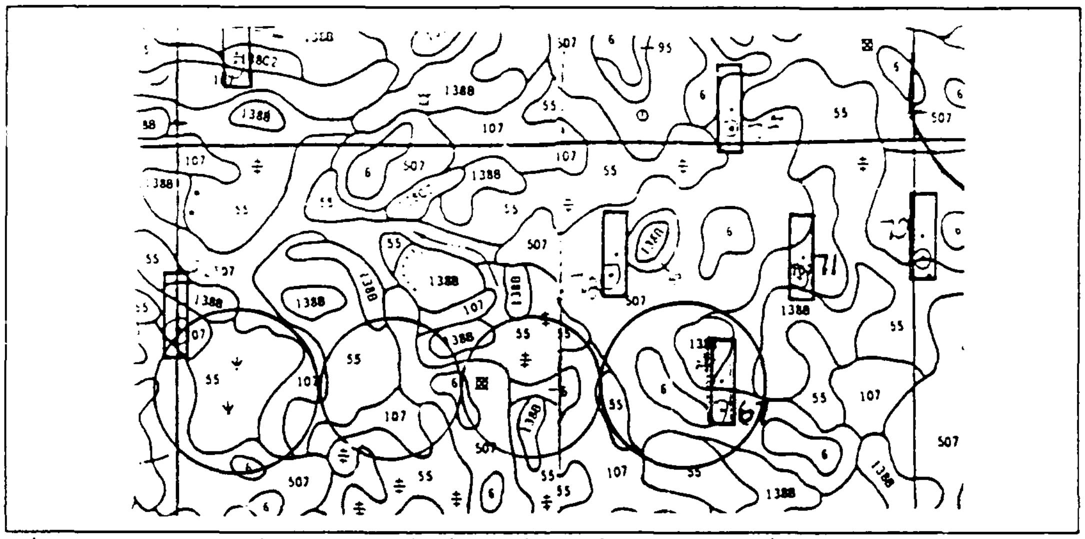

Figure 5. Soil Identification in Footprints

Volumetric Soil Moisture Percentage. This value was calculated in the same manner as the previous analysis.

Field Capacity Moisture Content. This value was calculated in the same manner as the previous analysis.

Beam Angle. This sub-grouping was established in the same manner as the previous analysis.

Field Orientation. An additional variable used in this analysis was the orientation of the furrowing in the vegetated fields. Fields were identified as having either north-south furrowing or east-west furrowing. This variable was chosen because the furrowing direction could alter the roughness affect on the microwave emission.

Weighted Values of the Independent Variables

An alternate approach to using the single, most centered footprint of each sample point in the analysis is the use of a weighted value. Initially, the weighting process that comes to mind is the use of all included footprints with an equal weighting factor. However, this process has been taken one step further in accuracy. Recall that the outlined beams of the PBMR are nearly circular. In Figure 3 (Chapter 2) the beam outlines are identified as the 3 dB levels for the sensor. This 3 dB level is equivalent to 1/2 the received signal level as compared to the beam center. The equation for converting to dB is y = 10 log x. So, assuming a beam strength of 1.0 in the center of the beam yields a value of 0.0 dB. A strength of .5 at the perimeter of the beam yields a value of -3.01 dB. Thus, the 3 dB perimeter is 1/2 the strength of the beam center. This information might lead one to believe that a sample located away from the center of the beam would send a signal that was weaker than one located at the center of a beam. This is a correct assumption. However, assuming a linear transition of signal strength from beam center to the beam perimeter would be in error. The beam signal strength for beam 1 is shown in Figure 6. All four beams are similar in the shape of the relative signal power curve. Notice that the beam strength drops to -3 dB at the 8 degree points on either side of beam center.

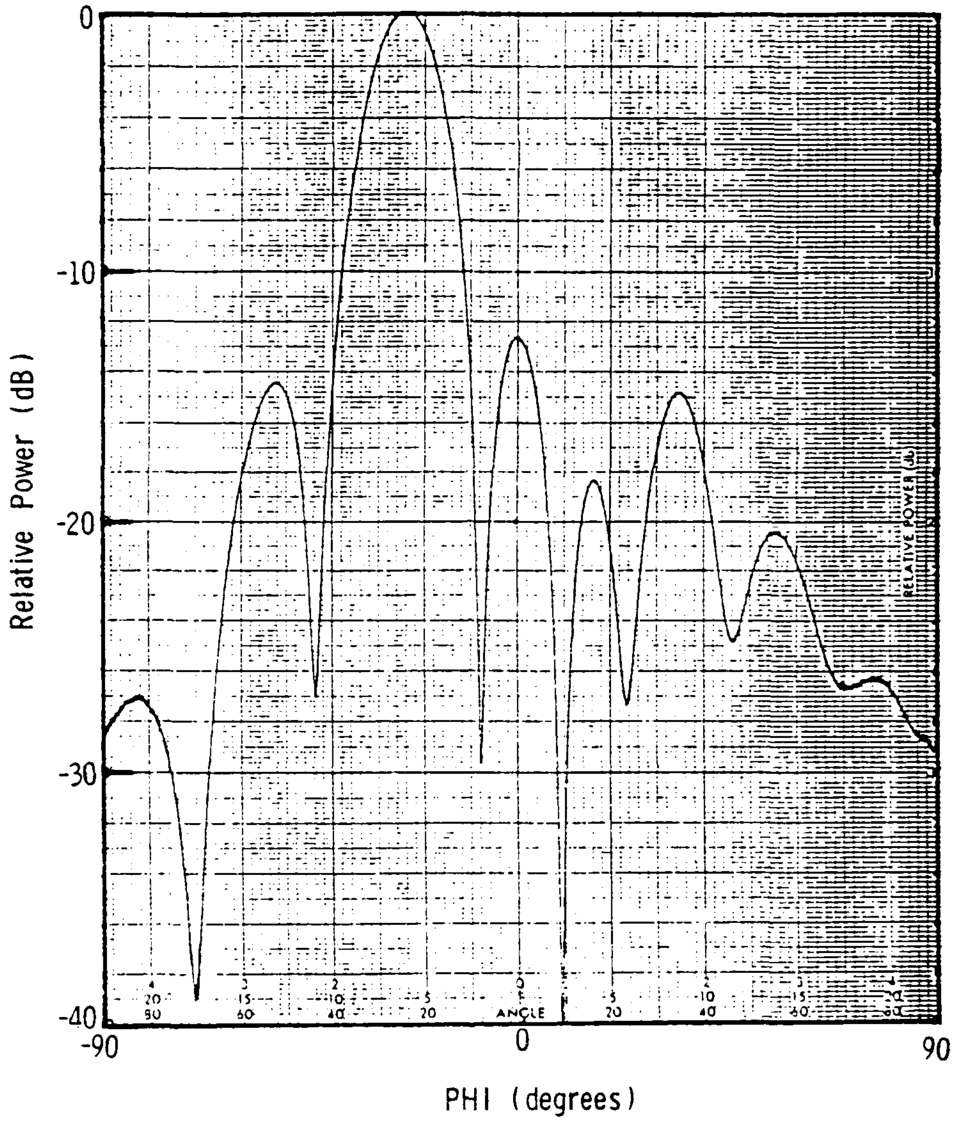

Figure 6. Relative Power vs. Angle for Beam 1 (10:53)

A good approximation of the curve shape is a Bessel function. The Bessel function values are delineated by 1/2 degrees from beam center in Table 3. These values correspond to the value of the beam strength at a certain angle from the beam center.

Table 3. Bessel Function Values vs. Angle from Beam Center

Bessel Function Value	Beam Angle (degrees)
1.0000	0.0
0.9975	0.5
0.9900	1.0
0.9777	1.5
0.9607	2.0
0.9391	2.5
0.9133	3.0
0.8836	3.5
0.8503	4.0
0.8138	4.5
0.7746	5.0
0.7331	5.5
0.6897	6.0
0.6450	6.5
0.5994	7.0
0.5534	7.5
0.5075	8.0

Using these values, the weight of each footprint was established using the following procedure:

1. The distance from the sample point to beam center was determined using the equation for a right triangle, $x^2 + y^2 = z^2$, where x is the north-south offset, y is the east-west offset, and z is the distance from beam center.

2. The angle from beam center to the sample point was determined geometrically using the aircraft altitude, the distance from the flight line to beam center, and the distance from the flight line to the sample point. A table displaying the conversion from flight line offset distance to angle from the beam center is below.

3. The Bessel function value for the associated angle was then chosen and recorded for the footprint.

Table 4. Sample Offset Angle vs. Distance from Flight Line

Sample Offset Angle (degrees)	Offset Distance Near-Nadir Beam (meters)	Offset Distance Far-Nadir Beam (meters)
0.0	75-80	241-247
0.5	70-75, 80-85	236-241, 247-253
1.0	65-70, 85-90	230-236, 253-259
1.5	60-65, 90-95	225-230, 259-265
2.0	55-60, 95-100	219-225, 265-271
2.5	50-55, 100-105	213-219, 271-277
3.0	45-50, 105-110	208-213, 277-283
3.5	40-45, 110-115	203-208, 283-289
4.0	36-40, 115-120	197-203, 289-295
4.5	31-36, 120-125	191-197, 295-301
5.0	27-31, 125-130	186-191, 301-307
5.5	22-27, 130-135	181-186, 307-313
6.0	17-22, 135-140	175-181, 313-320
6.5	12-17, 140-145	170-175, 320-326
7.0	7-12, 145-150	165-170, 326-333
7.5	2-7 , 150-155	160-165, 333-340
8.0	0-2 , 155-160	155-160, 340-343

4. After all footprints for a particular sample site were assigned their Bessel function values, those values were then used to weight the particular footprint.

5. The Bessel values were totaled, and each value was then normalized by that total.

In this way, the true weight of each footprint was determined. Using these weighting factors, then, the weighted average of the independent variables - thermal brightness, soil temperature (PRT5), bulk density, percent sand, and percent clay - were established. Appendix F shows the results of the weighting process.

Analysis Methods

A number of different analysis methods will be used in obtaining the results for Chapter 4. These methods include basic linear multiple regression, the use of dummy or indicator variables, utilization of the weighted values as described above, basic hypothesis testing using both R^2 and F values, and scatter and distribution plots of the data. Additionally, analysis of variance, variance-covariance analysis, and some limited residual analysis will be performed. A brief description of each of these methods follows.

Linear Multiple Regression. Multiple regression is a technique used to describe the relationship between a number of independent variables and a dependent variable. Each of the independent variables has a regression coefficient that describes its change for each unit change of the dependent variable. Formally, the regression model is described by the following equation:

$$Y_i = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + \ldots + e_i \qquad (5)$$

where

Y_i = the value of the dependent variable for trial i
B_0 = the y axis intercept for the curve
B_i = the regression coefficients for each independent variable
X_i = the value of the independent variables for trial i
e_i = the error term associated with the model

Dummy or Indicator Variables. Sometimes it is not possible to quantify the value of a variable. For example, field orientation can be either north-south or east-west.

This is a qualitative variable. In order to evaluate the affect this variable has on a model, some numeric value must be assigned to this qualitative factor. The method that will be used in this research is to assign a value of either 0 or 1 to the variable. This variable then becomes an indicator variable. The meaning of the regression parameters in a proposed model, then, is a measure of the affect that the indicator variable has on the dependent variable (13:328-331).

<u>R^2 and Adjusted R^2</u>. R^2 is a value that is a natural measure of the effect of the independent variables in reducing the variation in the dependent variable. This value is called the coefficient of multiple determination. It has a value between 0 and 1. It is defined as the proportionate reduction of total variation associated with the use of the independent variables X_i. So, as R^2 approaches 1, the more the total variation in Y is reduced by the introduction of the independent variables X_i. Values approaching 0 indicate just the opposite. So, a large value of R^2 indicates that a proposed regression model is a good fit. The term r^2 is used with simple regression models while the term R^2 is used with multiple regression models. (13:96-97, 241-242).

The adjusted coefficient of multiple determination takes into account the increase in the number of independent variables. Without accounting for this increase, the value of R^2 would always increase with additional independent variables. So, the value of the adjusted R^2 can actually decrease when an additional independent variable is added. This value is a more realistic evaluation of the fit of a model (13:241-242).

F Test. The F test statistic will be used as a method of determining the aptness of a linear regression model, just as the R^2 value is used. The test statistic $F* = MSR/MSE$, is the regression mean square divided by the residual or error mean square of the model. This value is compared to F distribution tables to indicate the aptness of the model.

Scatter Plots. Scatter plots are XY axis plots of two or more data sets. These plots help the researcher to determine the likelihood of a relationship between two variables.

Distribution Plots. Distribution plots help the researcher determine whether or not a certain distribution is a good fit for a given set of values.

Analysis of Variance. An analysis of variance table, generated for a regression model, contains the elements necessary to compute the F* value as well as the R^2 value. It is a compilation of all the error terms from the model and allows for the testing of individual elements of a regression model as well as testing of the entire model.

Variance-Covariance Matrix, Simple Correlation Matrix. The variance-covariance matrix is a compilation of the individual variances for each of the variables in the regression model. It also contains the covariance between each of the variables in the model. This covariance is a measure of the correlation between two independent variables. The correlation between two independent variables is important because a high correlation will give a false picture of the effect of an independent variable on the dependent variable. This effect is called multicollinearity.

Another useful matrix is the simple correlation matrix, which is a transformation of the variance-covariance matrix. The simple correlation matrix gives r^2 values for each pairing of variables, which identifies those variables that are correlated (13:271-278).

Residuals. Residuals are the algebraic difference between the observed values and the fitted model values. The analysis of residuals is important in determining the aptness of a fitted regression model. If the residuals reflect the properties assumed for residual values, then the model is apt. However, if the residuals do not follow these assumed properties, then problems with the model's aptness may be determined through the analysis of the inconsistencies (13:109-110).

IV. Analysis and Results

Regression analysis is the primary tool utilized in analyzing the data set. The data set is considered in many different configurations in an attempt to locate a correlated relationship between the microwave thermal brightness readings and the in situ soil moisture samples. This chapter explains the analysis in a sequential fashion, beginning with an explanation of the proposed model. Further, this chapter delineates the analysis itself, including results as appropriate. Finally, the best choice for the data is identified.

The Proposed Model

"Regression analysis is a statistical tool that utilizes the relation between two or more quantitative variables so that one variable can be predicted from the other, or others (13:23). Considering previous research in passive microwave sensing, it is logical that the model chosen conform to current knowledge. As the microwave emission has been shown to be affected by various factors, the model given in Equation (5) is a good general expression of the expected relationship. Specifically, the proposed model is:

$$Y_i = B_0 + B_1X_1 + \Sigma B_iX_i + e_i \qquad (6)$$

where

Y_i = the dependent variable - microwave thermal brightness or potentially the normalized emissivity.

B_0 = a the y-axis intercept.

B_1X_1 = the independent variable, some form of soil moisture and its corresponding regression coefficient.

ΣB_iX_i = additional independent variables and their regression coefficients which include soil vegetative cover, soil bulk density, soil texture, field orientation, beam orientation, and time.

e_i = the error term associated with the discrepancy between the actual relationship and the proposed model which represents it.

With this model as a basis, testing began to identify which of the independent variables, if any, had a strong linear relationship with the dependent variable, thermal brightness/emissivity.

Analysis

The analysis was done in two parts, considering two separate sets of data. These sets were the basic data set, using the most centered footprint, and the weighted data set, using the weighted values as described in the methodology. Additionally, after all the variables were considered for each set, time was included as a variable as a potential source of error. Also, the data sets were broken down into flight line groupings, in an attempt to identify if discrepancies in procedure contributed to error in the data set.

The Basic Data Set. The basic 58 point data set is depicted in Appendix E. An example of scatter plots of thermal brightness vs. gravimetric soil moistures is depicted below.

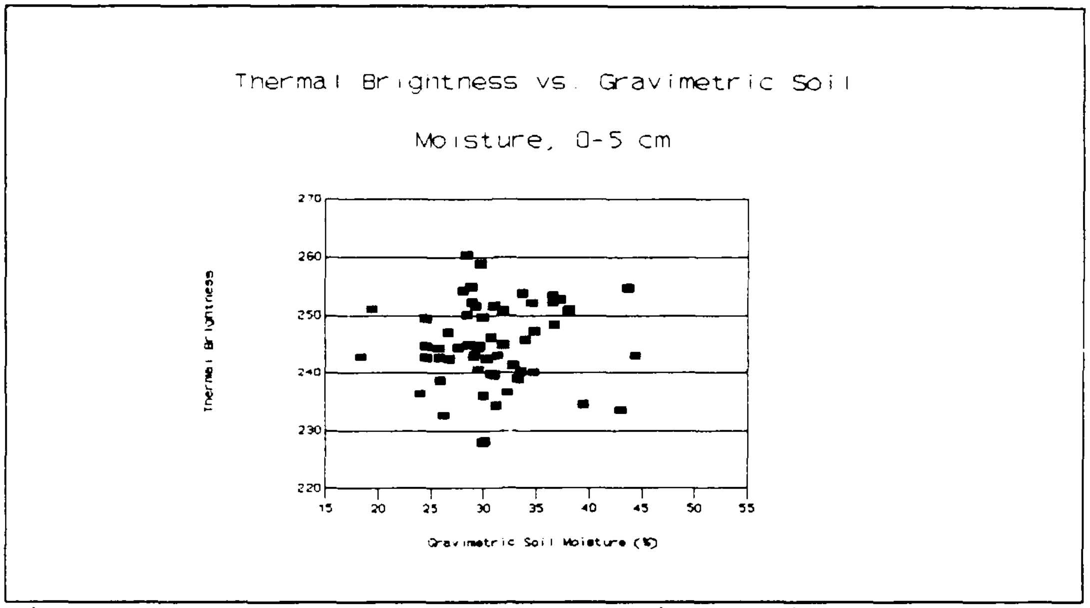

Figure 7. Scatter Plot of Regression Variables

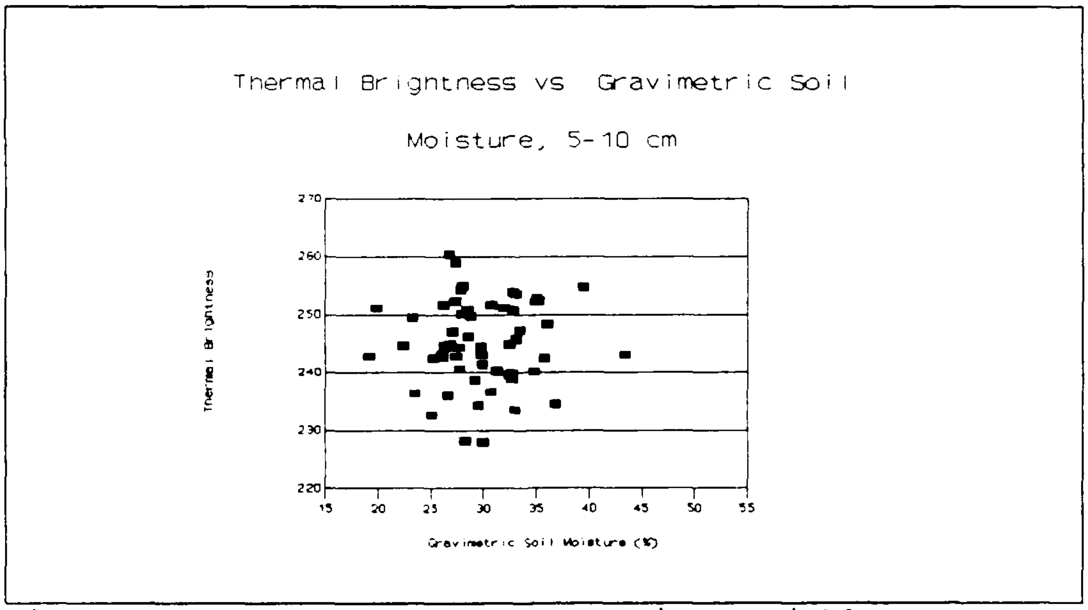

Figure 8. Scatter Plot of Regression Variables

Additional plots of thermal brightness/emissivity vs. gravimetric, volumetric, and field capacity are extremely similar to those shown here, revealing no further information. These plots all indicate that there are no significant relationships evident. A simple regression analysis of each of the moisture subsets versus the thermal brightness/emissivity proves that this observation is true. Included below in Table 5 are all the r^2 and F values for the simple regression performed on the scatter plot combinations identified above.

Table 5. Regression Values for All Basic Data Set Variables

Dependent Variable	Independent Variable	(cm) Depth	r^2 Value	F Value
Thermal Brightness	Gravimetric	0-5	.0041	.2279
Thermal Brightness	Gravimetric	5-10	.0014	.0762
Thermal Brightness	Volumetric	0-5	.0196	1.1190
Thermal Brightness	Volumetric	5-10	.0174	.9930
Thermal Brightness	Field Capacity	0-5	.0329	1.9070
Thermal Brightness	Field Capacity	5-10	.0291	1.6770
Emissivity	Gravimetric	0-5	.0091	.5144
Emissivity	Gravimetric	5-10	.0041	.2331
Emissivity	Volumetric	0-5	.0277	1.5940
Emissivity	Volumetric	5-10	.0238	1.3660
Emissivity	Field Capacity	0-5	.0399	2.3260
Emissivity	Field Capacity	5-10	.0338	1.9560

Both the r^2 values and the F values indicate that there is no significant relationship between the variables. A statistical test for determining whether or not there is a linear association between the dependent variable and the independent variable is performed using the F value listed in the table above. The alternatives in the test are:

$$H_0: B_1 = 0$$
$$H_a: B_1 \neq 0$$

The importance of testing whether or not $B_1 = 0$ is that if $B_1 = 0$ than there is no association between the variables. The decision rule is:

$$\begin{array}{l} \text{If } F^* \leq F(1-\alpha;p-1,n-p)\text{, conclude } H_0 \\ \text{If } F^* > F(1-\alpha;p-1,n-p)\text{, conclude } H_a \end{array}$$

All the listed regressions have the same values for p-1 and n-p, 1 and 56 respectively. So, choosing the largest F^* value is the same as choosing the best model of the group to test. In this case, $\alpha = .1$ is chosen. The decision rule is then:

$$\begin{array}{l} \text{If } F^* \leq F(.9,1,56)\text{, conclude } H_0 \\ \text{If } F^* > F(.9,1,56)\text{, conclude } H_a \end{array}$$

The value of F(.9,1,56) is 2.79. So, the appropriate conclusion is that H_0 is the correct choice and $B_1 = 0$, indicating that there is no linear relationship present between these variables. In order to ensure that the regression models developed for the data is fit properly, an analysis of the residuals is performed.

The residuals for each of the models were identified and plotted against the independent variable to identify nonlinearity of the regression function, indicate nonconstancy of error variance, and to identify outliers. Shown below in Figures 9 and 10 are examples of two of these scatter plots. The residuals meet the assumptions of a good linear model. Outliers were identified in both the volumetric soil moisture and the field capacity soil moisture. After removal of these outliers, the regression

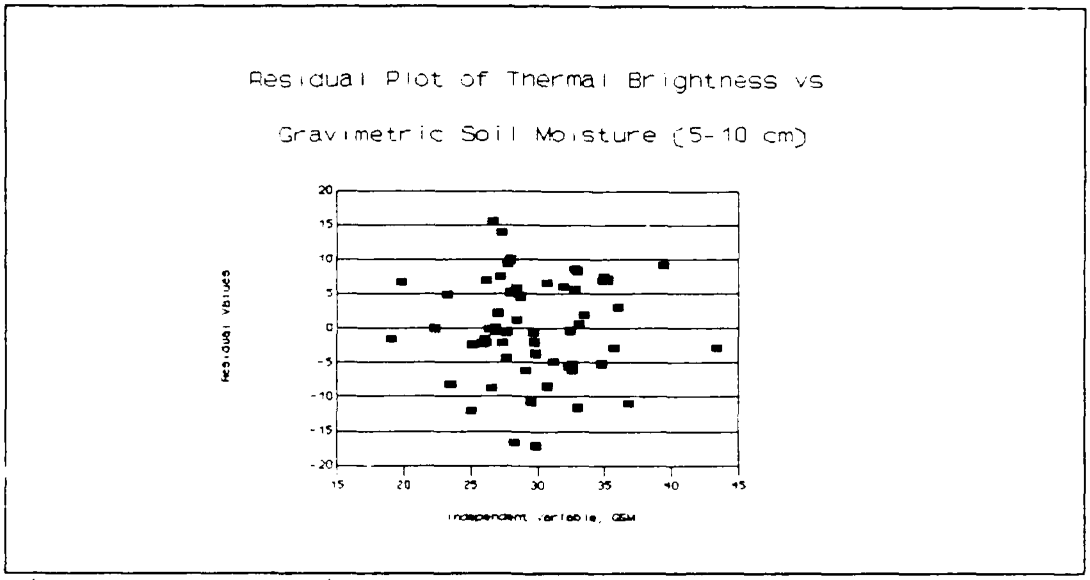

Figure 9. Residual Plot of Thermal Brightness vs. Gravimetric Soil Moisture

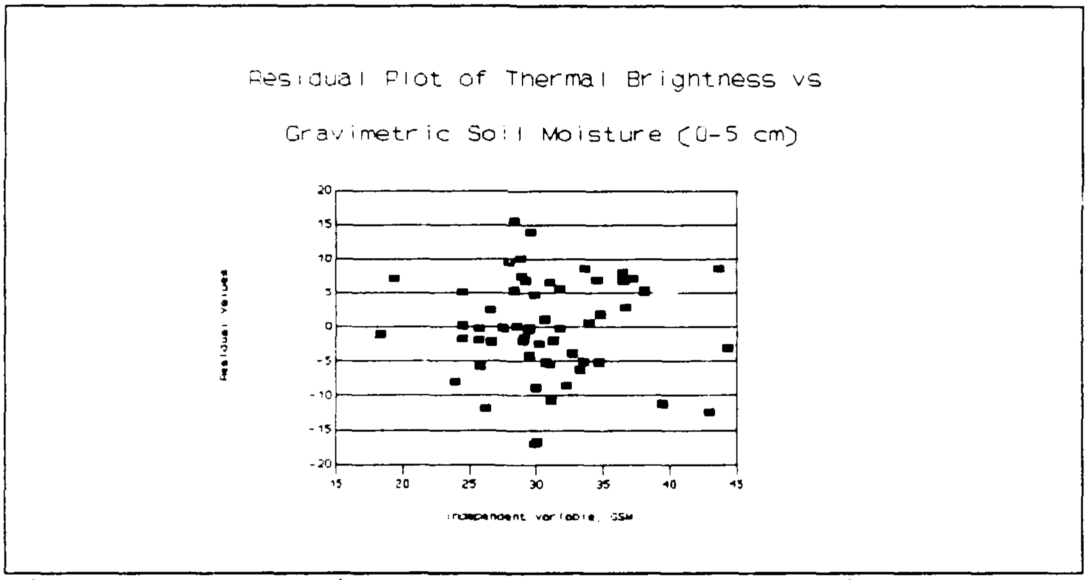

Figure 10. Residual Plot of Thermal Brightness vs. Gravimetric Soil Moisture

was reevaluated to determine the effect of the outliers. The regression did not change, indicating that the outliers had no appreciable affect on the data. Again, the balance of the residual plots show no great difference from the examples displayed above.

Finally, Wilk-Shapiro values were calculated for each of the residual sets and are shown below in Table 6. These values are a measure of the normality of the error terms. A value above .90 indicates that the error terms are normal and, thus, are acceptable.

Table 6. Wilk-Shapiro Values for Basic Data Set Residuals

Dependent Variable	Independent Variable	(cm) Depth	Wilk-Shapiro Value
Thermal Brightness	Gravimetric	0-5	.9840
Thermal Brightness	Gravimetric	5-10	.9845
Thermal Brightness	Volumetric	0-5	.9827
Thermal Brightness	Volumetric	5-10	.9837
Thermal Brightness	Field Capacity	0-5	.9843
Thermal Brightness	Field Capacity	5-10	.9847
Emissivity	Gravimetric	0-5	.9860
Emissivity	Gravimetric	5-10	.9863
Emissivity	Volumetric	0-5	.9821
Emissivity	Volumetric	5-10	.9823
Emissivity	Field Capacity	0-5	.9819
Emissivity	Field Capacity	5-10	.9803

The residual analysis of these regression curves shows that the aptness of each is high. However, since not one of the relationships was even remotely strong, this information is not helpful in identifying a more significant relationship.

In review of the statistical evidence, it is apparent that the gravimetric soil moisture values taken at the 5-10 cm depth are less correlated with the microwave readings than the 0-5 cm values in every case. So, the deeper soil moisture values will be discarded from further analysis in the basic data set.

As the simple regression analysis of the data points showed no good relationship, the next step was to separate the variables of soil texture, soil bulk density, and soil thermal temperature from the soil moisture values. Recall that the volumetric soil moisture was found using the soil bulk density and the field capacity was found using the volumetric soil moisture, the percent clay, and the percent sand. Emissivity was calculated using the soil thermal temperature.

<u>Separated Variables</u>. In order to explain the change in thermal brightness values for the sample sites, variables other than the soil moisture are now considered. Vegetative cover, soil bulk density, soil texture in the form of percent sand and percent clay, field orientation, beam orientation, and the soil thermal temperature were added to the model. At first, only those variables that had quantitative values were added to the model. So, vegetative cover, field orientation, and beam orientation were held out. The results of the regression subset analysis is shown below in Table 7. These variables provided some insight into the correct model, but again, no strong relationship was found. The R^2 values and Adjusted R^2 values indicate a weak relationship at best. In order to verify that we again were using correct models, several of the better regression relationships were examined in detail from each group.

Table 7. All Possible Subset Regression Models for TB1

Independent Variables: (A)GRAV1 (B)PRT51 (C)BD1 (D)SAND1 (E)CLAY1

Adjusted R Square	R Square	Resid SS	Model Variables
0.0000	0.0000	2.954E+03	INTERCEPT ONLY
-0.0137	0.0041	2.942E+03	A
-0.0162	0.0194	2.897E+03	A B
0.0340	0.0849	2.703E+03	A B C
0.0218	0.0904	2.687E+03	A B C D
0.0132	0.0997	2.659E+03	A B C D E
0.0010	0.0186	2.899E+03	B
0.0515	0.0847	2.704E+03	B C
0.0483	0.0650	2.762E+03	C
0.0317	0.0656	2.760E+03	A C
0.0160	0.0678	2.754E+03	A C D
0.0332	0.0671	2.756E+03	C D
-0.0044	0.0132	2.915E+03	D
-0.0192	0.0165	2.905E+03	A D
-0.0145	0.0389	2.839E+03	A B D
0.0037	0.0387	2.840E+03	B D
0.0396	0.0902	2.688E+03	B C D
0.0315	0.0995	2.660E+03	B C D E
-0.0101	0.0431	2.827E+03	B D E
-0.0181	0.0176	2.902E+03	D E
-0.0056	0.0120	2.919E+03	E
-0.0021	0.0331	2.856E+03	B E
0.0489	0.0990	2.662E+03	B C E
0.0431	0.0766	2.728E+03	C E
0.0253	0.0766	2.728E+03	C D E
0.0077	0.0773	2.726E+03	A C D E
0.0260	0.0773	2.726E+03	A C E
-0.0196	0.0161	2.906E+03	A E
-0.0332	0.0212	2.891E+03	A D E
-0.0288	0.0434	2.826E+03	A B D E
-0.0198	0.0339	2.854E+03	A B E
0.0312	0.0991	2.661E+03	A B C E

Again, a residual analysis was performed to identify the aptness of the models. The same testing procedure was used. The results of this analysis indicated that the models used were correct. A summary of the Wilk-Shapiro and F values are listed below in Table 8.

Table 8. Summary of F Values and Wilk-Shapiro Values for "Best" Subset Regression Models

Dependent Variable	Independent Variables	F Value	W-S Value
Thermal Brightness	PRT5/Bulk Density	2.546	.9839
Thermal Brightness	PRT5/Bulk Density/% Clay	1.977	.9849
Thermal Brightness	Bulk Density	3.892	.9837
Thermal Brightness	Bulk Density/% Clay	2.282	.9872
Emissivity	Grav (0-5)/Bulk Density	1.887	.9802
Emissivity	Bulk Density	3.621	.9811
Emissivity	Bulk Density/% Sand	1.793	.9816
Emissivity	Bulk Density/% Clay	2.063	.9826

The number of variables in the models evaluated above vary from one to three. Using the same criteria for testing the linear association between the independent variables and the dependent variables as before yields the following information:

For $p-1 = 1$, $n-p = 56$, the best F value is 3.892
For $p-1 = 2$, $n-p = 55$, the best F value is 2.546
For $p-1 = 3$, $n-p = 54$, the best F value is 1.977

The corresponding value for $F(.9,1,56) = 2.79$
The corresponding value for $F(.9,2,55) = 2.39$
The corresponding value for $F(.9,3,54) = 2.18$

So, for the one and two variable cases there is at least an indication of some linear relationship. Finally, the introduction of the qualitative variables was performed.

Qualitative Variables. The qualitative variables introduced were coded in the form of indicator variables. The coding is shown in Appendix E. These four variables were evaluated in a regression format. The results of this analysis indicated that land use and east-west beam orientation were slightly correlated. However, the degree of correlation was quite small. These results are summarized in Table 9. A look at the F values again gives the indication that the best models are slightly correlated. The F value at (.9,4,53) = 2.04, showing a linear relationship does exist. Despite this small correlation, an attempt was made to evaluate the data without the interference of the heavy vegetation and with each beam orientation separated. Regressions were performed on the variables and the summary of the subset regressions are listed in Table 10. Although there are better correlations evident in these evaluations, none are very significant.

Weighted values. Usin,' the weighted values rather than the most centered footprints, an identical analysis was performed. An evaluation of this set showed that there was

Table 9. Summary of r^2 and F Values for Simple and Multiple Regressions of Coded Indicator Variables

Independent Variables: (A)GRAV1 (B)PRT5 (C)BD1

Indicator Variables: (D)Land Use (E)Beam Orientation (Near-Far Nadir) (F)Field Orientation (N-S,E-W) (G)Beam Orientation (East or West)

F Value	R Square	Adjusted R Square	Model Variables
2.138	.1389	.0739	ABC D
1.270	.0874	.0186	ABC E
1.269	.0874	.0185	ABC F
1.946	.1281	.0623	ABC G
2.606	.0445	.0274	D
.322	.0057	-.0120	E
.159	.0028	-.0150	F
2.836	.0482	.0312	G

Table 10. Results of "Best" Simple and Multiple Regression Models of Basic Set Minus Vegetative or Beam Orientation Affects

Independent Variables: (A)GRAV1 (B)PRT51 (C)BD1 (D)Beam Orientation (E)Land Use

Adjusted R Square	R Square	Model Variables	Less
0.0669	0.1114	B C	Corn
0.0607	0.1278	B C D	Corn
0.0840	0.2457	A C E	East Beam
0.1295	0.2319	C E	East Beam
0.1312	0.1823	E	East Beam
0.0994	0.2054	A E	East Beam
0.0734	0.1824	B E	East Beam
0.0686	0.2330	B C E	East Beam
0.0625	0.1106	B C	West Beam
0.0586	0.1310	B C E	West Beam

a slight improvement in the strength of the relationships, but not enough of an increase to consider it statistically important. Depicted in Figures 11 and 12 below are two representative scatter plots.

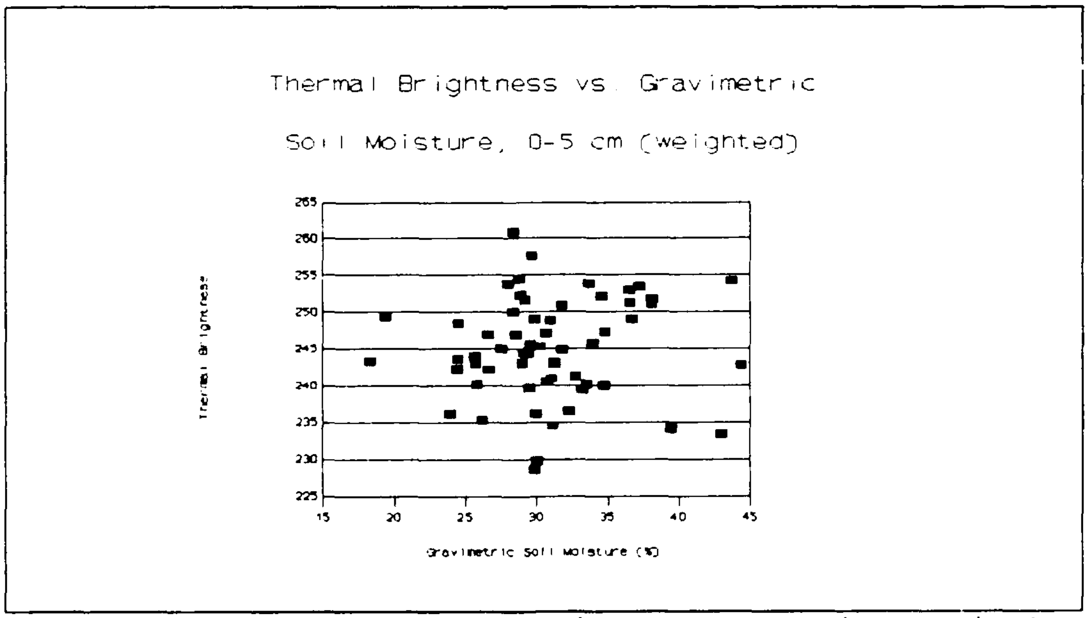

Figure 11. Scatter Plot of Weighted Regression Variables

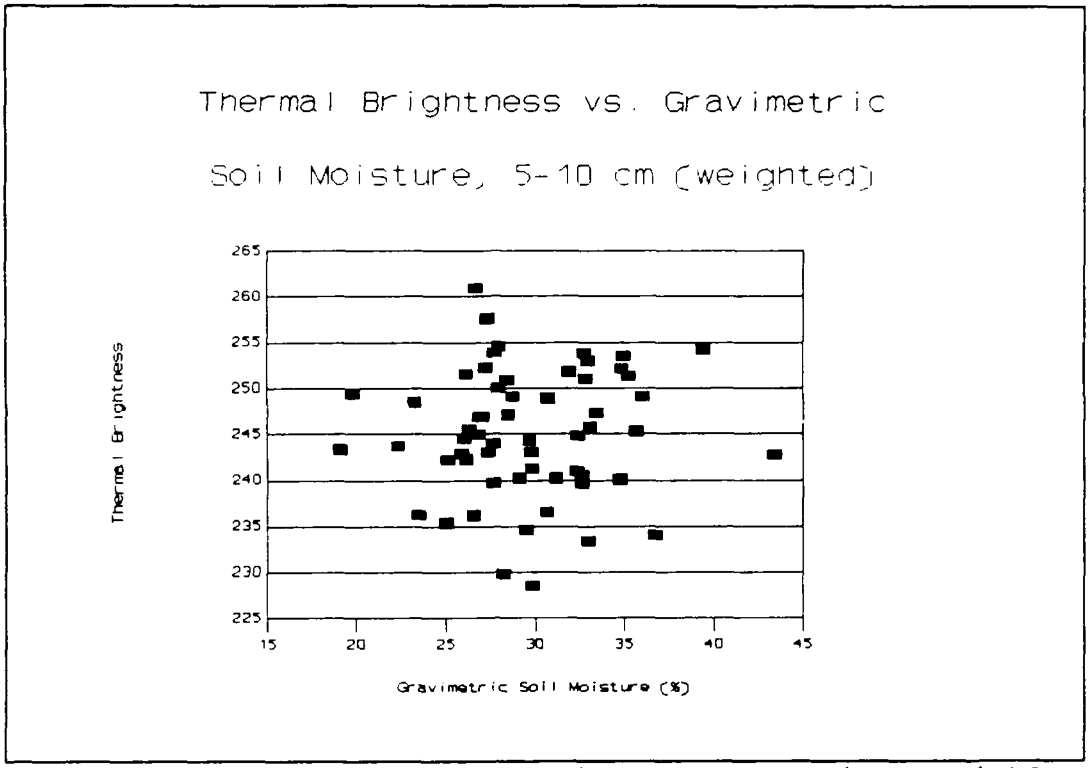

Figure 12. Scatter Plot of Weighted Regression Variables

Shown below in Table 11 is a summary of the F and r^2 values for the regression curves.

Table 11. Simple Regression Results for All Weighted Data Set Variables

Dependent Variable	Independent Variable	(cm) Depth	r^2 Value	F Value
Thermal Brightness	Gravimetric	0-5	.0040	.2257
Thermal Brightness	Gravimetric	5-10	.0022	.1223
Thermal Brightness	Volumetric	0-5	.0184	1.0490
Thermal Brightness	Volumetric	5-10	.0181	1.0300
Thermal Brightness	Field Cap.	0-5	.0353	2.0500
Thermal Brightness	Field Cap.	5-10	.0343	1.9890
Emissivity	Gravimetric	0-5	.0102	.5750
Emissivity	Gravimetric	5-10	.0067	.3803
Emissivity	Volumetric	0-5	.0284	1.6360
Emissivity	Volumetric	5-10	.0275	1.5810
Emissivity	Field Cap.	0-5	.0445	2.6100
Emissivity	Field Cap.	5-10	.0420	2.4540

As before, a residual analysis was performed. This analysis showed no problems with any of the residual assumptions. So, again, our chosen models are acceptable. As with the unweighted data set, all the scatter plots and residual plots were nearly identical.

Again, the gravimetric soil moisture values taken at the deeper sampling depth are less correlated. These were not considered in the rest of the analysis.

Separated Variables. Including the separated variables in the analysis was done in the same manner. Table 12 shows the results of the subset regression analysis. Notice that there are no outstanding improvements over the unweighted data, although the values of R^2 are slightly higher in the "better" models. Individually, both bulk density and sand are more correlated in the unweighted data set than the weighted set. However, in both sets of data, the bulk density is much more correlated that any other variable. This leads to the conclusion that the increase in the values of correlation of the simple regressions going from gravimetric to volumetric to field capacity is a result of the bulk density alone. It is apparent that in both the unweighted and weighted sets the gravimetric soil moisture decreases the strength of the relationship. Representative subset regression curves were chosen for further analysis. Neither the F value nor the residual analysis showed any sign of an improved relationship. Table 13 shows the summarized Wilk-Shapiro values as well as the F values. The same indicator variables used in the basic data set were then introduced into the weighted data set.

Table 12. All Possible Subset Regression Models for TB2

Independent Variables: (A)GRAV1 (B)PRT52 (C)BD2 (D)SAND2 (E)CLAY2

Adjusted R Square	R Square	Resid SS	Model Variables
0.0000	0.0000	2.706E+03	INTERCEPT ONLY
-0.0138	0.0040	2.695E+03	A
-0.0163	0.0194	2.654E+03	A B
0.0277	0.0789	2.493E+03	A B C
0.0148	0.0840	2.479E+03	A B C D
0.0246	0.1102	2.408E+03	A B C D E
0.0013	0.0188	2.655E+03	B
0.0453	0.0788	2.493E+03	B C
0.0431	0.0599	2.544E+03	C
0.0268	0.0610	2.541E+03	A C
0.0101	0.0622	2.538E+03	A C D
0.0270	0.0612	2.541E+03	C D
-0.0074	0.0103	2.678E+03	D
-0.0224	0.0135	2.670E+03	A D
-0.0162	0.0373	2.605E+03	A B D
0.0022	0.0372	2.605E+03	B D
0.0328	0.0837	2.480E+03	B C D
0.0430	0.1101	2.408E+03	B C D E
0.0042	0.0567	2.553E+03	B D E
-0.0036	0.0316	2.621E+03	D E
0.0135	0.0308	2.623E+03	E
0.0185	0.0529	2.563E+03	B E
0.0606	0.1100	2.408E+03	B C E
0.0548	0.0880	2.468E+03	C E
0.0393	0.0899	2.463E+03	C D E
0.0227	0.0913	2.459E+03	A C D E
0.0387	0.0893	2.464E+03	A C E
0.0001	0.0352	2.611E+03	A E
-0.0179	0.0356	2.610E+03	A D E
-0.0143	0.0568	2.552E+03	A B D E
0.0009	0.0535	2.561E+03	A B E
0.0429	0.1101	2.408E+03	A B C E

Table 13. Summary of F Values and Wilk-Shapiro Values for "Best" Subset Regression Models

Dependent Variable	Independent Variables	F Value	W-S Value
Thermal Brightness	PRT5/Bulk Density	2.352	.9851
Thermal Brightness	Bulk Density	3.566	.9878
Thermal Brightness	Bulk Density/%Clay	2.653	.9906
Thermal Brightness	PRT5/Bulk Dens/%Clay	2.226	.9893
Emissivity	Bulk Density	3.369	.9880
Emissivity	Bulk Density/%Clay	2.412	.9883

<u>Qualitative Variables</u>. The introduction of qualitative variables into the analysis showed that with the weighted data, the correlation was smaller. From the F Values in Table 14, it is apparent that none of the combinations of indicator variables show any linear relationship at all.

Table 14. Summary of r^2 and F Values from Simple and Multiple Regressions of Coded Indicator Variables

Weighted Independent Variables: (A)GRAV1 (B)PRT5 (C)BD2

Indicator Variables: (D)Land Use (E)Beam Orientation (Near-Far Nadir) (F)Field Orientation (N-S, E-W) (G) Beam Orientation (East or West)

F Value	R Square	Adjusted R Square	Model Variables
1.931	.1272	.0613	ABC D
1.234	.0852	.0161	ABC E
1.140	.0792	.0098	ABC F
1.406	.1181	.0341	ABC G
2.219	.0381	.0209	D
.463	.0082	-.0095	E
.639	.0011	-.0167	F
1.896	.0404	.0191	G

Despite the lack of evidence to support further investigation of these factors, regressions were performed on the data set with certain portions of the information eliminated. The results of this analysis are depicted in Table 15. As was predicted by the lack of correlation in the indicator variables, eliminating the corn had a limited impact on the relationship. Of note is that in no case did a regression done with some form of soil moisture produce any significant results.

Table 15. Results of "Best" Simple and Multiple Regression Models of Weighted Data Minus Vegetative Affects

Dependent Variables: (A)Thermal Brightness (B)Emissivity
Independent Variables: (C)Bulk Density (D)PRT5 (E)%Clay

Adjusted R Square	R Square	Dependent Variable	Independent Variables	Less
.0305	.0590	A	C	Corn
.0452	.1014	A	CD	Corn
.0668	.1113	A	CE	Corn
.0932	.1580	A	CDE	Corn
.0532	.0983	B	CE	Corn

<u>Time</u>. Time was considered as a variable to determine if any variance was associated with the sequential collection of the data. There are several reasons for evaluating time as a variable. Potentially, there could be calibration errors associated with the data that arise from computer hardware inconsistencies. Also, the precipitation that fell during the data collection might effect the variance of the data. This variance would tend to show up

in a time analysis, as the affect of the rain on the soil moisture, and hence the thermal brightness readings, would be cumulative. To perform this portion of the analysis, the data points were sequenced numerically by order of collection and also using absolute differences in sampling times. In the first case, all samples were considered as equally spaced in time. In the second case, the samples were evaluated in absolute time. The first sample taken was assigned a time of 0.0 minutes. All others were given times relative to that first sample. As shown in Figures 13 and 14, scatter plots of the thermal brightness vs. the two time sequences showed no problem with variance. To verify that variance was statistically unchanged, another F test was computed. The null hypothesis in this test was that the variance was unchanged between the first five flight lines and the last flight line. A confidence interval using α = 0.02 was established. This interval was .36 to 3.91. The variance was computed at 106.29 for Flight Line 6 and as 40.55 for the other five flight lines. The ratio of the two variances is 2.62. As 2.62 falls within the bounds of the confidence interval, we accept the null hypothesis that the variance is unchanged from the first five flight lines to Flight Line six. Evidently, the rain that fell, particularly during the last flight line, was not a source of increased variance in the experiment.

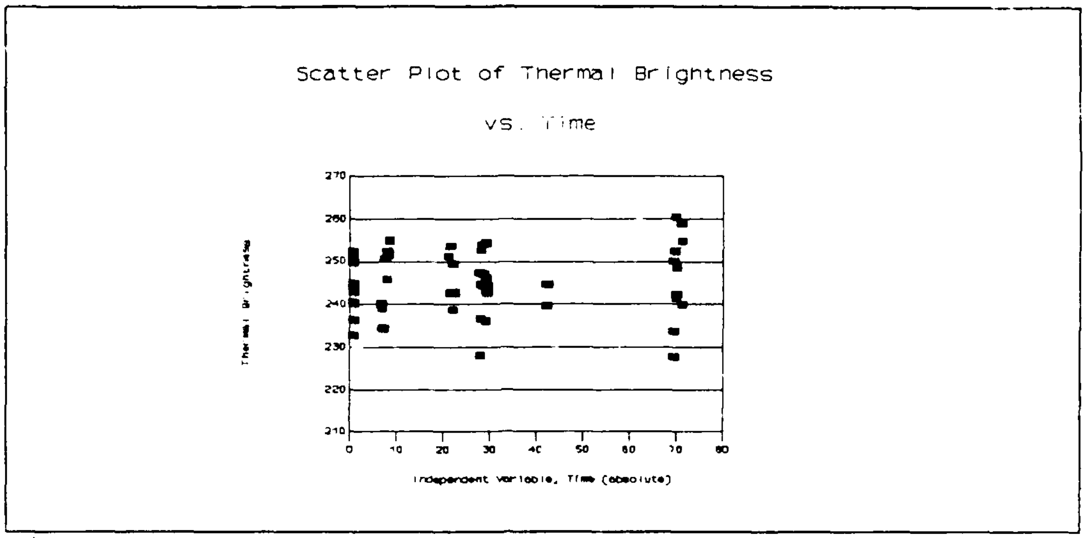

Figure 13. Scatter Plot of Thermal Brightness vs. Time (Absolute)

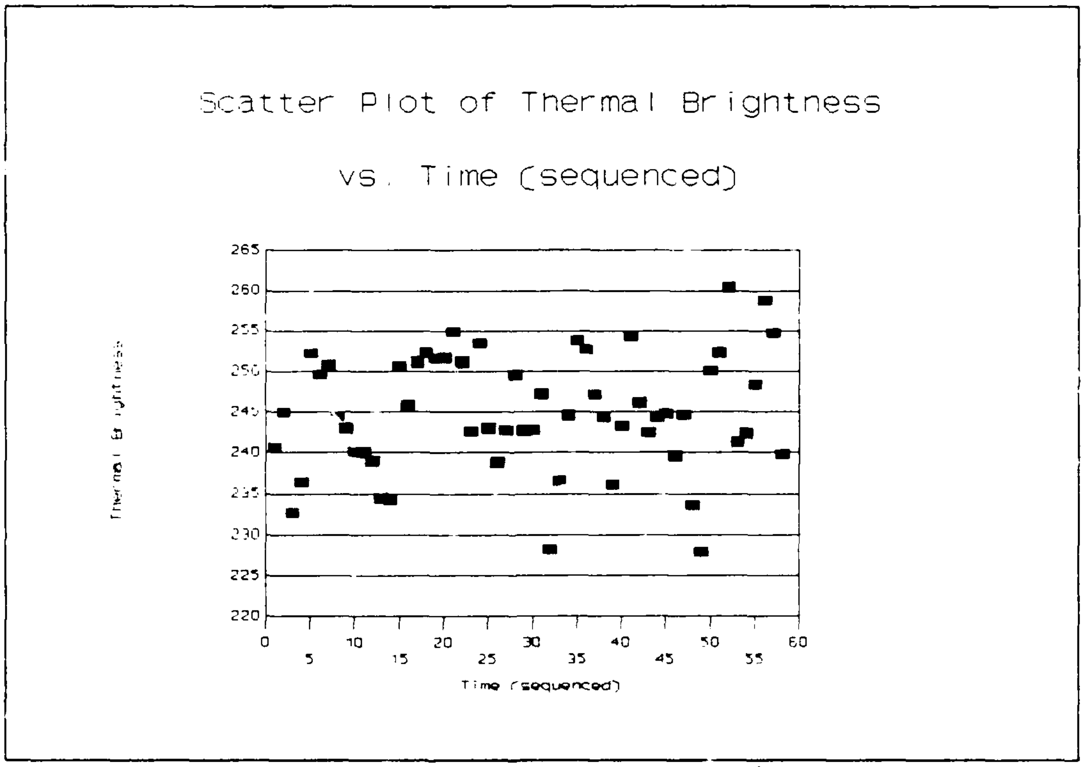

Figure 14. Scatter Plot of Thermal Brightness vs. Time (Sequenced)

Additionally, a scatter plot of residuals showed no problem with variance. The variance is not particularly changed indicating that time is apparently not an important variable.

Separating the Flight Lines. A final attempt to find a stronger relationship between soil moisture and the microwave sensor readings was performed by breaking down the sample sites into the flight lines in which they were collected. Each flight line was regressed using all the previous methods. The reason for evaluating the individual flight lines is again a question of variance errors. Knowing that precipitation was falling most heavily during the last two flight lines, there seemed to be a possibility

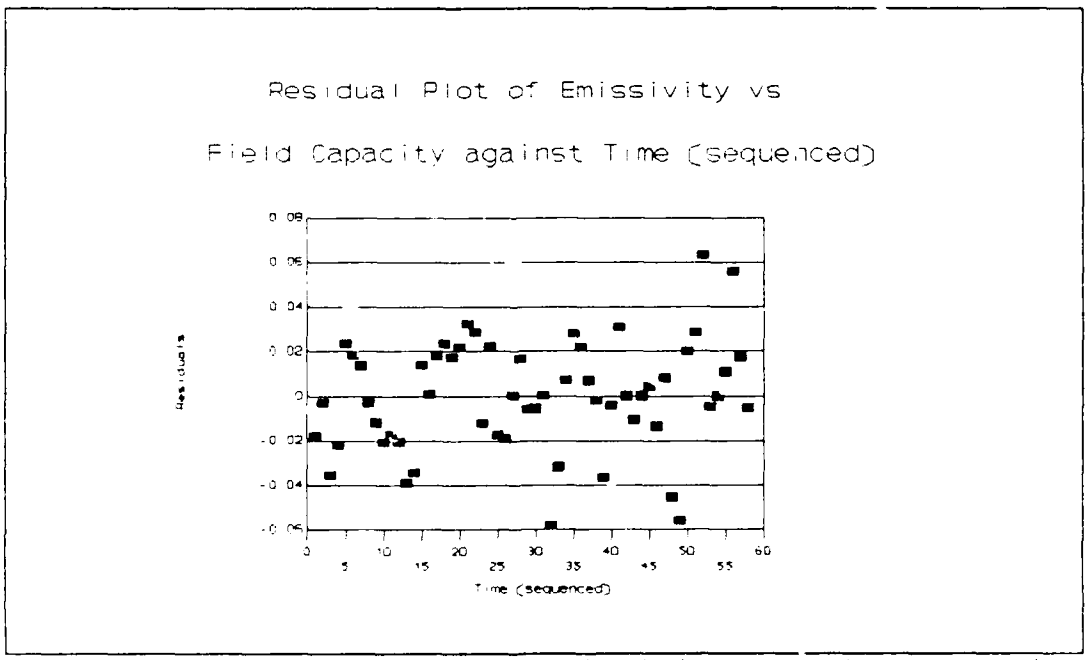

Figure 15. Residual Plot of Emissivity vs. Field Capacity Against Time (Sequenced)

that the relationship within the first few flight lines was being masked by the later flight lines. Also, as the only two flight lines that were positioned correctly with certainty were those that included the roads, there was a possibility that these two flight lines would give better results than the others. However, neither of these was the case. Flight Line 2, alone, showed the proper relationship. There appears to be no reason that Flight Line 2 had the proper relationship. There are no inconsistencies in the Flight Line 2 variables as compared with the other flight lines. None of the other flight lines were close to providing the hoped for relationship. A compilation of all pertinent figures is included in Appendix G. Statistically, the number of points in any of the flight lines is too small to be a good representation of the data set as a whole. So, no really important information was found in this part of the analysis.

Results

The proposed model contained both soil moisture and other variables that might affect the variance of the dependent variable. In a model that shows a strong relationship between microwave emission and soil moisture it is quite possible to have results such as suggested by the proposed model. However, the models which produced the best correlation did not include soil moisture in any of its forms. Therefore, when choosing the best model, those models with additional variables were eliminated. The choice of the best model came from the simple regression models between the dependent variable, thermal brightness/emissivity and the independent variable, any form of soil moisture. Returning to the values given in the early portion of this chapter, it was shown that no test statistic value between those variables was significant enough to say that a linear relationship existed.

V. Conclusions and Recommendations

Conclusions

There were absolutely no results that would indicate a linear relationship between soil moisture and the microwave response of the PBMR. However, this does in no way indicate that there is no such relationship. Rather than concluding that the results were negative, it is more proper to say that the results were inconclusive. The reasons for the lack of results are summarized below in the listed sources of error.

Sources of Error

The experiment and analysis had many potential sources of error. In this section a breakdown of each of these sources of error and possible solutions are presented.

Experimental Error. Within the experiment procedure a number of potential errors existed. These were:

1. Location of sampling points on the ground. Students were asked to locate points on the ground based on a set of field notes. The problem with this procedure is the difficulty entailed in moving distances as far as 1200 meters without making a mistake. Only people very experienced in land navigation are accurate to within 40 meters when moving a distance that great. Certainly the students may have located the majority of the points at the correct locations, but most probably this was a fairly large

source of error.

2. The overflight of the aircraft. Certainly a very difficult thing to do is maintain a constant speed and heading when flying over an area with very few landmarks. This became quite evident to this researcher during the review of the color videotape of the flight. The aircraft did not stay on a flight line for more than a few miles at a time without drifting. This problem is not correctable. The movement of the aircraft caused problems in the data processing that will be explained later.

3. The aircraft flight plan. The researchers who set up the experiment determined that a minimum of 80 sample points were necessary to perform a statistically sound analysis. However, only 58 points were actually sampled. The problem was that the aircraft failed to fly over the identified sample locations. Somehow, the people controlling the experiment failed to correctly lay out the watershed boundaries for the pilots. Not only were many locations missed because the aircraft did not make enough passes to the east, but several sampling locations were missed because the flight lines were cut off before the most northern points were reached. This error is easily corrected by the careful identification of the experimental area to the aircraft crew.

4. Data collection. Through a literature review, numerous factors affecting the passive soil moisture sensing

were identified. Some of these variables were not evaluated because required data were not collected. These variables were vegetative biomass, which can aid in accounting for the heavy interference provided by the land cover and surface roughness measurements which can aid in accounting for the unequal emission of the microwave light at the sample locations.

5. Sample location choices. Although a perfectly good technique for sample location identification was used, it may have been more effective to change the sampling pattern. Each footprint was approximately 170 meters in diameter. Wide variations in soil moisture can exist in areas one tenth that size. In order to get an accurate measure of the in situ moisture, a number of samples could have been taken within the footprint area and then averaged. It is entirely possible that many of the samples called ground truth are not representative of the footprint as a whole. Relating the sampling technique to the footprint size must be a consideration in any experiment of this type.

6. Sequential sampling over time. In order to provide a better data set, a point brought out in Wilson's report is repeated here. The most effective means of getting a thorough evaluation of soil moisture response of a microwave radiometer is to ensure that there is a wide range of moisture values to examine. The easiest way to accomplish this wide range is to sample the experimental area over a

number of days. Most preferably, this should be accomplished following a good rain, so that as the soil dries, values can be related to the changes.

Another source of error related to the soil moisture was the small range of values that existed on the day of sampling. Although no evidence was presented in Wilson's report, an evaluation of this source of error is presented here. Figure 16 shows a histogram distribution of the soil moisture. A Wilk-Shapiro value of .9647 indicates that the distribution was normal and that the range was probably not adequate to ensure a good regression analysis.

Table 16. Histogram of Gravimetric Soil Moisture (0-5 cm)

```
  LOW      HIGH
       N
---------------
  17.0     21.0 |*****
         2      |*****
  21.0     25.0 |**********
         4      |**********
  25.0     29.0 |*********************************
        14      |*********************************
  29.0     33.0 |**********************************************
        21      |**********************************************
  33.0     37.0 |************************
        10      |************************
  37.0     41.0 |**********
         4      |**********
  41.0     45.0 |*******
         3      |*******
```

Of course, as the experiment was not a dedicated one, many of these factors were most likely unable to be controlled. Choice of the day or time of flight was not available to the researchers as it would be in a dedicated experiment. Also, the main purpose of the experiment was not to identify a quantitative soil moisture to microwave response relationship, but to create a digitized representation of the relative moisture content of the whole watershed based on the thermal brightness readings (23).

Data Processing Error. This section will explain the errors associated with the processing of the data after collection. Enumerated below are the major contributing error sources from this side of the analysis.

1. Linking of the footprint to the sample site. This was without question the largest problem faced by the researcher. As mentioned above, the flight line of the aircraft was not perfect in either speed or direction. In the cases of the two flight lines that were over roads, this was not a problem. However, the identification of the exact location of the aircraft, and thus the location of the footprints was not possible when the plane was over open fields. Every sample site that was not within view of a road is a potential source of error. Flight lines were determined by location of landmarks, but with normal aircraft drifting, the location could be off by as much as 50 meters. That distance is enough to place a sample point in another footprint. For the first four flight lines accuracy in locating ground landmarks was good. However, over the last two flight lines, particularly the last, the potential for

extreme error existed. It is possible that errors in location of up to 150 meters occurred in identifying footprints. Almost no landmarks were available to place these last two flight lines in relation to the sample sites.

A potential correction to this problem is the placement of some type of beacon on the ground that would identify to the viewer its exact location. Several low cost, reusable identification markers exist and could easily be altered for this purpose.

2. Measurement error. Even after identifying the flight line, error in measurements is another source of error. Locating the sample points on both the USGS 1:24,000 map and the Soil Survey 1:15,480 map is accurate only to size of the pencil lead and the placement of the mapping template. Human error can be large in this case, as much as 20 meters in placement. Eliminating this error entirely is not possible, however reducing the error through specialized equipment is possible. Special drafting equipment and trained personnel can be much more accurate than the untrained researcher in this area.

3. Identification of Soils. As mentioned above, mapping the soils from the footprints is fraught with potential error. This error is made greater by the difficulty in perfect identification of the percentage of a particular soil in a footprint. This researcher made estimates based on a visual rather than a numerical calculation. Potentially, the error

in this part of the evaluation can be reduced through the use of specialized equipment which can digitize the information and process it through computer software.

4. Multicollinearity. To identify whether any of the variables were biased, a simple correlation matrix was developed. This is displayed below in Table 17.

Table 17. Simple Correlation Matrix for Basic Data Set Variables

	GRAV1	GRAV2	PRT51	BD1	SAND1	CLAY1	CLU
GRAV1	1.0000						
GRAV2	0.9022	1.0000					
PRT51	-0.2571	-0.2204	1.0000				
BD1	0.1510	-0.0091	0.0170	1.0000			
SAND1	0.0507	0.0657	0.1809	0.2748	1.0000		
CLAY1	0.0045	-0.0825	-0.0778	-0.0066	-0.4321	1.0000	
CLU	0.0399	0.0293	0.1557	0.0191	-0.0614	0.1788	1.0000
CBOA	0.0573	0.1208	-0.0762	-0.1391	-0.0732	-0.2137	0.1386
CFO	-0.1483	-0.1314	-0.0263	-0.0357	-0.1400	0.1470	-0.0560
CBOB	-0.1212	-0.1517	0.0906	0.1030	0.1227	-0.0356	0.0293

	CBOA	CFO	CBOB
CBOA	1.0000		
CFO	-0.1152	1.0000	
CBOB	-0.1260	-0.3708	1.0000

It is apparent, based on the values above, that there are no problems with multicollinearity as the largest r^2 value is well below what would be considered unacceptable. For correlation to start becoming a problem the value of r^2 must be greater than 0.6. The correlation between the two depths of soil moisture is expected, thus both of these variables were not used in the same model. Notice that the correlation between some of the variables is much better than any between soil moisture and the microwave readings.

Recommendations

What follows is a list of recommendations based on the results of the thesis effort.

1. Research should continue to occur in this field. Poor results in this experiment are linked more to experimental procedure error than to the lack of a relationship.

2. The weighting process, developed in this thesis effort, has the potential to produce some good results. Utilizing the process with data that is more correlated should give a much better evaluation of its utility.

3. Changes in experimental procedure should be undertaken to ensure that the next analysis has a reasonable chance of producing results that are significant.

Appendix A: Field Notes of Sample Site Locations

Site #	E-W Distance (feet)	N-S Distance (feet)	Reference Point
1	160 E	600 S	NW corner, Sec 22
2	600 E	800 S	NW corner, Sec 22
3	1460 E	800 S	NW corner, Sec 22
4	4000 E	100 S	NW corner, Sec 22
5	360 W	800 S	NE corner, Sec 22
7	1000 E	420 S	NW corner, Sec 23
10	1040 W	1400 S	NE corner, Sec 23
15	720 W	300 S	NE corner, Sec 23
17	1260 W	1620 N	NE corner, Sec 23
18	2200 E	900 N	SW corner, Sec 15
19	720 E	500 N	SW corner, Sec 15
20	730 E	640 N	SW corner, Sec 15
21	40 W	1520 N	SW corner, Sec 15
22	250 W	2280 N	SW corner, Sec 15
23	2430 E	1200 N	SW corner, Sec 15
24	150 W	3600 N	SE corner, Sec 15
25	700 E	3600 N	SE corner, Sec 15
26	580 E	4520 N	SE corner, Sec 15
31	260 E	1400 N	NE corner, Sec 15
32	1960 W	400 N	NE corner, Sec 15
33	2400 W	30 S	NE corner, Sec 15
34	960 E	200 N	NW corner, Sec 15
35	0	1000 N	NW corner, Sec 15
36	1280 E	1400 N	NW corner, Sec 15
37	1600 E	1540 N	NW corner, Sec 15
38	2650 E	2100 S	NW corner, Sec 10
39	1400 E	1820 S	NE corner, Sec 10
40	2000 E	2950 S	NE corner, Sec 10
45	1000 W	100 N	SE corner, Sec 3
46	2520 W	200 N	SE corner, Sec 3
47	660 E	400 S	SW corner, Sec 3
48	80 W	80 N	SW corner, Sec 3
49	80 W	400 N	SW corner, Sec 3
50	1140 W	1520 N	SE corner, Sec 3
51	60 E	1200 N	SE corner, Sec 3
54	2020 E	1800 S	NW corner, Sec 2
55	440 E	2500 S	NW corner, Sec 2
56	1880 E	2400 S	NW corner, Sec 3
57	2600 E	1400 N	SW corner, Sec 34
58	3740 E	360 N	SW corner, Sec 34
59	4280 E	380 N	SW corner, Sec 34
61	2800 E	800 N	SW corner, Sec 35
62	1300 W	200 N	SE corner, Sec 35
64	920 W	2600 N	SE corner, Sec 34
66	0	1300 S	NE corner, Sec 34
67	1360 W	1800 S	NE corner, Sec 35
72	2100 W	900 S	NE corner, Sec 35
74	400 E	600 N	SE corner, Sec 27

Site #	E-W Distance (feet)	N-S Distance (feet)	Reference Point
75	1280 W	80 N	SE corner, Sec 26
78	1920 E	3020 N	SW corner, Sec 26
80	220 W	3160 N	SW corner, Sec 26
81	1080 W	2300 N	SW corner, Sec 26
83	2360 W	2600 N	SW corner, Sec 26
84	2120 E	3600 N	SW corner, Sec 27
85	2840 E	4320 N	SW corner, Sec 27
86	2080 W	3960 N	SE corner, Sec 26
87	1500 W	4400 N	SE corner, Sec 26
88	300 E	180 N	NE corner, Sec 27

Appendix B: Soil Texture and Bulk Density Average Values

Soil Mapping Unit	Bulk Density	Percent Sand	Percent Clay
6	1.275	7.0	38.5
52E2	1.45	32.0	34.0
55	1.20	32.0	29.5
95	1.375	30.0	30.0
107	1.375	20.0	30.5
138B	1.425	32.0	21.0
138C2	1.425	37.0	21.0
138D2	1.425	37.0	21.0
221	0.35	3.0	0
259	1.25	32.0	24.0
308	1.4	35.0	24.0
335	1.375	35.0	21.0
348	1.325	30.0	18.5
485B	1.5	35.0	22.0
507	1.3	20.0	31.0
511	0.6	10.0	25.0
524	1.425	35.0	16.0
640E2	1.45	60.0	16.0
641E2	1.425	45.0	21.0
655	1.375	30.0	25.0
659	1.3	37.0	22.5
811	0.155	3.0	0
823B	1.525	65.0	14.0
1595	1.15	3.0	28.5
5040	1.4	17.0	45.0

These values have been extracted from the Hancock County, Iowa Soil Survey. They are average values; individual soils can have ranges up to 40% in both sand and clay while the range for bulk density can be as great as 0.2.

Appendix C: Multibeam 1.4 GHz Pushbroom Microwave Radiometer

The following summary is from the NASA Technical Memorandum entitled "Design and Development of a Multibeam 1.4 GHz Pushbroom Microwave Radiometer". The PBMR is a Dicke radiometer. "A Dicke radiometer is one in which the receiver is alternately switched between the desired input signal and a reference noise source" (9:2). Effectively, this process allows for the cancellation of the effects of the receiver noise. This is very important in view of the small signal received passively in the 1.4 GHz range of the electromagnetic spectrum. A table highlighting the specifications of the PBMR is shown below.

Table C-1. Specifications of 1.4 GHz PBMR (9:17)

Frequency	1413 MHz	
Bandwidth	25 MHz	
Integration Time	0.5 seconds	
Sensitivity	1.0 kelvin	
Accuracy	2.0 kelvin	
Polarization	Horizontal	
	3-Beam	4-Beam
Resolution Cell*	290-570 ft	200-260 ft
Swath Width*	1400 ft	750 ft

*500 ft altitude using 9 dB contour

The antenna used in the PBMR is a 64-element (8x8) array which produces multiple (four) beams. The radiation pattern is approximately circular, although with increasing distance from nadir the beam becomes more and more oblated. For this experiment, the outside portion of the far-nadir beam was 12 meters wider than the inner portion of the same beam. On the near-nadir beam, the difference was less than 2 meters.

The PBMR provides four nearly simultaneous readings of the microwave signal within each beam. In addition, it provides a single average soil thermal temperature for each group of four beam values. The computer which runs the PBMR collects all the data on a formatted tape recorder while also providing a time value for each reading.

The PBMR has been used extensively by NASA and other groups investigating microwave emission over the past five years.

Appendix D: Summary of Results from Original Analysis Including Evaluations of Variables for Affect on Thermal Brightness

VARIABLE	N	Mean	St. Dev.	Range	value of t* or H** level of significance (if better than .20)
Geometry					
west-looking beam (all footprints)	7	253.13	3.13	247.6-258.5	H = 10.43
west nadir beam	12	245.40	5.79	234.3-254.0	better than .02 level
east nadir beam	17	245.80	6.65	234.2-256.8	
east-looking beam	22	243.76	7.12	230.4-261.8	
west-looking beam (without corn)	4	251.25	2.41	247.6-254.2	H = 8.89
west nadir beam	10	244.27	5.55	234.3-251.3	better than .05 level
east nadir beam	15	244.55	6.06	234.2-256.8	
east-looking beam	18	241.64	5.44	230.4-251.6	
two nadir beams (all footprints)	29	245.6	6.31	234.2-256.8	t = 0.22
two off-nadir beams	29	246.0	7.54	230.4-261.8	
two nadir beams (without corn)	25	244.44	5.86	234.2-256.8	t = 0.37
two off-nadir beams	22	243.4	6.24	230.4-254.2	
Surface Cover					
SPOT 7/17/87 land cover (footprints with homogeneous land cover):					
beans	20	246.20	5.62	234.3-256.8	H = 18.63
corn	11	253.88	4.22	245.8-261.8	better than .001 level
unclassified	5	239.28	6.14	230.4-247.6	
footprints with road (without	12	243.34	5.88	234.3-251.6	t = 0.39
footprints without road corn)	35	244.15	6.11	230.4-256.8	
normalized brightness temperature:					
footprints with road (without	12	0.828	0.020	0.797-0.857	t = 0.58
footprints without road corn)	35	0.834	0.021	0.788-0.885	
Soils					
footprints with soil homogeneous for texture class, no corn, no road:					
loam SMUs	4	247.2	3.56	243.3-252.3	t = 1.16
clay loam SMUs	10	244.78	3.12	240.1-250.7	
same as above, including road footprints:					
loam SMUs	8	246.78	4.61	237.3-252.3	t = 1.55
clay loam SMUs	15	243.81	3.93	234.3-250.7	about .16 level
soil association 2 (without corn	24	243.33	5.94	234.1-254.2	t = 1.85
soil association 3 or road)	10	246.05	6.40	234.2-256.8	about .08 level
soil association 2 (without corn,	33	243.65	5.82	230.4-254.2	t = 1.24
soil association 3 including road)	11	246.24	6.13	234.2-256.8	
drainage class somewhat "poor" or worse	13	244.11	5.11	234.1-252.3	t = 1.09
drainage class "poor" or better (footprints with known soils, no corn, no road)	12	246.63	5.92	234.2-256.8	
drainage class "somewhat "poor" or worse	20	244.10	5.19	234.1-252.3	t = 1.16
drainage class "poor" or better (same as above, including roads)	15	246.39	6.10	234.2-256.8	
bulk density 1.3 or less	17	243.86	5.64	234.1-254.2	t = 1.61
bulk density greater than 1.3 (footprints with known soils, no corn, no road)	7	247.86	4.32	242.5-256.8	about .11 level
bulk density 1.3 or less	21	244.26	5.74	234.1-254.2	t = 0.78
bulk density greater than 1.3 (same as above, including roads)	13	245.85	5.38	234.3-256.8	

* Difference-of-means t-test
**Kruskal-Wallis analysis of variance with ranks

Appendix E: Compilation of All Basic Data Set Variables

Table E-1: Soil and Soil Moisture Values

Site Number	(0-5 cm) GSM	(5-10 cm) GSM	Percent Sand	Percent Clay	Bulk Density
1.0000	28.530	26.840	37.000	22.500	1.3000
2.0000	29.480	27.660	33.600	23.800	1.3100
3.0000	28.790	27.960	22.200	20.000	1.3550
4.0000	19.400	19.810	26.000	30.000	1.2880
5.0000	25.690	27.640	33.000	28.000	1.2800
7.0000	30.220	35.680	27.400	15.200	1.1400
10.000	30.710	32.620	18.500	24.350	0.9100
15.000	43.670	39.400	43.100	20.600	1.4350
17.000	29.620	27.300	33.300	26.250	1.3000
18.000	29.180	26.130	27.700	21.700	1.2830
19.000	26.160	25.040	9.8000	27.300	1.1800
20.000	23.920	23.460	12.000	29.630	1.2250
21.000	34.550	34.830	26.000	30.250	1.2500
22.000	29.850	28.740	32.000	29.500	1.2000
23.000	30.960	30.700	30.200	19.600	1.3130
24.000	30.630	28.460	32.000	26.300	1.3250
25.000	28.000	27.730	32.000	26.200	1.2580
26.000	29.090	26.040	27.200	30.200	1.2580
31.000	29.960	26.550	39.800	22.000	1.3200
32.000	36.510	32.970	32.600	27.500	1.3850
33.000	25.730	25.880	34.200	22.000	1.3690
34.000	28.870	27.220	33.700	26.350	1.3650
35.000	38.050	32.820	26.000	30.000	1.2880
36.000	38.110	31.900	23.600	30.200	1.3230
37.000	33.930	33.080	31.000	24.000	1.2500
38.000	44.330	43.380	32.000	24.000	1.2500
39.000	31.040	32.340	33.100	28.850	1.2580
40.000	31.790	32.390	22.900	29.450	1.3630
45.000	25.810	29.100	32.000	30.300	1.3400
46.000	18.300	19.070	32.000	26.850	1.2430
47.000	27.530	26.800	22.100	30.400	1.3580
48.000	31.240	29.750	32.000	30.500	1.3580
49.000	33.520	31.160	30.800	29.500	1.2100
50.000	24.470	23.220	32.000	29.500	1.2000
51.000	29.420	29.670	32.000	30.000	1.2880
54.000	29.520	26.300	13.500	34.750	1.2880
55.000	26.570	27.000	28.400	28.900	1.2750
56.000	31.770	28.410	29.600	22.900	1.4150
57.000	31.120	29.490	30.800	29.600	1.2180
58.000	28.980	27.360	26.000	30.200	1.2500
59.000	24.450	26.120	26.000	29.150	1.3100
61.000	26.670	25.100	26.000	30.000	1.2880
62.000	36.670	36.010	27.200	27.350	1.3380
64.000	37.200	34.960	27.200	29.950	1.2630
66.000	33.660	32.760	21.200	30.700	1.3130
67.000	32.730	29.800	19.900	30.700	1.3180

Table E-1: Soil and Soil Moisture Values (con't)

Site Number	(0-5 cm) GSM	(5-10 cm) GSM	Percent Sand	Percent Clay	Bulk Density
72.000	28.320	26.650	21.200	30.850	1.2900
74.000	24.470	22.310	28.200	25.650	1.3830
75.000	36.530	35.210	22.300	31.300	1.2680
78.000	28.340	27.940	26.000	30.000	1.2880
80.000	30.030	28.210	32.000	27.380	1.2560
81.000	32.250	30.670	31.800	25.400	1.3230
83.000	39.450	36.750	23.400	30.600	1.2880
84.000	33.240	32.610	32.000	29.700	1.2350
85.000	34.720	34.740	20.000	31.000	1.3000
86.000	29.850	29.870	26.000	30.000	1.2880
87.000	42.950	32.960	22.400	30.300	1.3400
88.000	34.770	33.420	21.200	30.550	1.3350

Table E-2: Sensor Readings and Calculated Emissivity

Site Number	Footprint Time	Thermal Brightness	PRT5	Emissivity
1.0000	16:24:18.4	244.90	20.500	0.8340
2.0000	16:24:16.5	240.60	20.500	0.8193
3.0000	16:32:40.3	254.90	20.000	0.8695
4.0000	16:45:30.3	251.10	20.500	0.8551
5.0000	16:53:44.3	244.30	20.400	0.8322
7.0000	16:53:42.4	242.50	20.500	0.8258
10.000	17:35:32.8	239.80	18.100	0.8233
15.000	17:35:28.4	254.70	17.900	0.8751
17.000	17:35:20.5	258.80	17.000	0.8920
18.000	16:32:34.4	251.70	20.200	0.8580
19.000	16:24:22.4	232.70	20.100	0.7935
20.000	16:24:22.9	236.40	20.100	0.8061
21.000	16:24:26.8	252.20	20.100	0.8600
22.000	16:24:29.8	249.60	19.800	0.8520
23.000	16:32:33.4	251.60	20.500	0.8568
24.000	16:53:27.6	246.10	20.800	0.8372
25.000	16:53:27.6	254.30	20.800	0.8651
26.000	16:53:24.1	243.20	20.200	0.8290
31.000	16:53:16.2	236.10	20.900	0.8029
32.000	16:45:54.0	253.50	19.800	0.8653
33.000	16:45:52.0	242.60	21.400	0.8236
34.000	16:32:18.1	252.30	20.000	0.8607
35.000	16:24:46.5	250.80	20.700	0.8535
36.000	16:32:13.7	251.10	19.500	0.8580
37.000	16:32:13.2	245.80	19.500	0.8399
38.000	16:46:05.3	243.00	19.500	0.8303
39.000	17:06:23.1	239.60	18.300	0.8221
40.000	17:06:18.2	244.80	18.100	0.8405
45.000	16:46:14.2	238.80	20.400	0.8135
46.000	16:46:14.7	242.80	20.500	0.8268
47.000	16:25:02.8	244.50	21.400	0.8301
48.000	16:25:04.8	243.00	21.400	0.8250
49.000	16:25:06.2	240.20	21.400	0.8155
50.000	16:46:19.6	249.50	21.600	0.8465
51.000	16:52:57.0	244.40	20.400	0.8326
54.000	17:06:44.3	244.70	18.400	0.8393
55.000	16:52:52.1	247.10	21.400	0.8389
56.000	16:31:48.0	250.70	20.100	0.8549
57.000	16:31:34.2	234.30	19.700	0.8001
58.000	16:46:35.9	242.80	20.400	0.8271
59.000	16:46:35.4	242.70	21.100	0.8248
61.000	17:34:20.8	242.40	18.300	0.8317
62.000	17:34:23.3	248.40	18.400	0.8520
64.000	16:52:33.2	252.70	20.400	0.8608
66.000	16:52:27.4	253.80	20.500	0.8643
67.000	17:34:10.0	241.30	17.300	0.8308
72.000	17:34:06.1	260.40	17.600	0.8956
74.000	16:52:20.5	244.60	18.100	0.8398

Table E-2: Sensor Readings and Calculated Emissivity (con't)

Site Number	Footprint Time	Thermal Brightness	PRT5	Emissivity
75.000	17:34:02.1	252.30	18.100	0.8663
78.000	17:33:49.8	250.10	20.000	0.8531
80.000	16:52:11.6	228.20	20.500	0.7771
81.000	16:52:14.6	236.60	20.000	0.8071
83.000	16:31:08.1	234.50	19.400	0.8016
84.000	16:31:05.1	239.00	19.700	0.8161
85.000	16:31:02.6	240.10	19.800	0.8196
86.000	17:33:45.8	227.90	19.700	0.7782
87.000	17:33:43.9	233.60	19.400	0.7985
88.000	16:52:02.8	247.20	21.900	0.8378

Table E-3: Calculated Volumetric and Field Capacity Values

Site Number	(0-5 cm) VSM	(5-10 cm) VSM	(0-5 cm) FC	(5-10 cm) FC
1.0000	37.089	34.892	113.28	106.57
2.0000	38.619	36.235	113.01	106.04
3.0000	39.010	37.886	111.80	108.57
4.0000	24.987	25.515	64.037	65.390
5.0000	32.883	35.379	90.314	97.169
7.0000	34.451	40.675	110.07	129.96
10.000	27.946	29.684	73.698	78.281
15.000	62.666	56.539	206.23	186.06
17.000	38.506	35.490	108.57	100.07
18.000	37.438	33.525	108.58	97.232
19.000	30.869	29.547	74.570	71.377
20.000	29.302	28.738	69.675	68.336
21.000	43.187	43.537	110.33	111.22
22.000	35.820	34.488	95.801	92.239
23.000	40.650	40.309	123.73	122.69
24.000	40.585	37.709	113.40	105.36
25.000	35.224	34.884	98.556	97.606
26.000	36.595	32.758	94.211	84.333
31.000	39.547	35.046	124.18	110.05
32.000	50.566	45.663	139.49	125.96
33.000	35.224	35.430	106.31	106.93
34.000	39.408	37.155	111.25	104.89
35.000	49.008	42.272	125.60	108.33
36.000	50.420	42.204	127.09	106.38
37.000	42.412	41.350	121.63	118.58
38.000	55.412	54.225	159.97	156.54
39.000	39.048	40.684	106.07	110.52
40.000	43.330	44.148	109.81	111.88
45.000	34.585	38.994	91.520	103.19
46.000	22.747	23.704	63.072	65.726
47.000	37.386	36.394	93.192	90.721
48.000	42.424	40.400	111.97	106.63
49.000	40.559	37.704	107.68	100.10
50.000	29.364	27.864	78.534	74.523
51.000	37.893	38.215	100.67	101.53
54.000	38.022	33.874	85.886	76.518
55.000	33.877	34.425	89.342	90.788
56.000	44.955	40.200	129.77	116.04
57.000	37.904	35.919	100.50	95.235
58.000	36.225	34.200	92.600	87.423
59.000	32.029	34.217	82.989	88.657
61.000	34.351	32.329	88.034	82.852
62.000	49.064	48.181	131.12	128.76
64.000	46.984	44.154	121.35	114.04
66.000	44.196	43.014	109.19	106.28
67.000	43.138	39.276	105.80	96.329
72.000	36.533	34.378	90.095	84.783
74.000	33.842	30.855	93.129	84.908
75.000	46.320	44.646	114.31	110.18

Table E-3: Calculated Volumetric and Field Capacity Values (con't)

Site Number	(0-5 cm) VSM	(5-10 cm) Vsm	(0-5 cm) FC	(5-10 cm) FC
78.000	36.502	35.987	93.547	92.226
80.000	37.718	35.432	103.82	97.528
81.000	42.667	40.576	120.58	114.67
83.000	50.812	47.334	127.29	118.58
84.000	41.051	40.273	109.50	107.42
85.000	45.136	45.162	110.36	110.42
86.000	38.447	38.473	98.531	98.597
87.000	57.553	44.166	143.89	110.42
88.000	46.418	44.616	114.90	110.44

Table E-4: Flight Line and Land Use Values

Site Number	Flight Line	Land Use	SPOT Land Use
1.0000	1	4.0000	10.000
2.0000	1/2	3.0000	7.0000
3.0000	2	1.0000	1.0000
4.0000	3	5.0000	10.000
5.0000	4	5.0000	7.0000
7.0000	4/5	5.0000	7.0000
10.000	6	1.0000	7.0000
15.000	6	4.0000	7.0000
17.000	6	1.0000	1.0000
18.000	2	2.0000	2.0000
19.000	1/2	6.0000	7.0000
20.000	1/2	6.0000	7.0000
21.000	1	8.0000	1.0000
22.000	1	1.0000	7.0000
23.000	2/3	2.0000	7.0000
24.000	4	1.0000	1.0000
25.000	4	1.0000	1.0000
26.000	4	7.0000	1.0000
31.000	4	1.0000	1.0000
32.000	3	1.0000	1.0000
33.000	3	3.0000	7.0000
34.000	1/2	2.0000	1.0000
35.000	1	4.0000	1.0000
36.000	2	1.0000	1.0000
37.000	2	1.0000	1.0000
38.000	2/3	1.0000	7.0000
39.000	5	3.0000	7.0000
40.000	5	1.0000	1.0000
45.000	3	3.0000	9.0000
46.000	2/3	1.0000	2.0000
47.000	1/2	1.0000	1.0000
48.000	1	1.0000	7.0000
49.000	1	1.0000	7.0000
50.000	3	2.0000	7.0000
51.000	4	2.0000	2.0000
54.000	5	1.0000	1.0000
55.000	4	3.0000	7.0000
56.000	2	1.0000	2.0000
57.000	2/3	7.0000	1.0000
58.000	3	1.0000	1.0000
59.000	3/4	1.0000	1.0000
61.000	5/6	5.0000	7.0000
62.000	6	1.0000	1.0000
64.000	4	2.0000	2.0000
66.000	4	2.0000	2.0000
67.000	6	2.0000	7.0000
72.000	6	2.0000	2.0000
74.000	4	6.0000	10.000
75.000	6	1.0000	1.0000

Table E-4: Flight Line and Land Use Values (con't)

Site Number	Flight Line	Land Use	SPOT Land Use
78.000	6	2.0000	1.0000
80.000	4	1.0000	7.0000
81.000	4	2.0000	2.0000
83.000	2	1.0000	7.0000
84.000	2	1.0000	1.0000
85.000	2	2.0000	1.0000
86.000	6	2.0000	2.0000
87.000	6	4.0000	1.0000
88.000	4	2.0000	2.0000

Land use values are designated in the key below:

1. Beans
2. Corn
3. Oats
4. Grass
5. Ripe Oats
6. Alfalfa
7. Unclassified
8. Green Oats
9. Bare Ground
10. Road
11. Forest

Table E-5: Indicator Variables

Site Number	Land Use	Beam Orient A	Field Orient	Beam Orient B
1.0000	0.0000	0.0000	0.0000	0.0000
2.0000	0.0000	1.0000	0.0000	0.0000
3.0000	0.0000	0.0000	0.0000	1.0000
4.0000	0.0000	0.0000	0.0000	1.0000
5.0000	0.0000	0.0000	0.0000	0.0000
7.0000	0.0000	1.0000	1.0000	0.0000
10.000	0.0000	1.0000	0.0000	0.0000
15.000	0.0000	1.0000	0.0000	0.0000
17.000	0.0000	1.0000	1.0000	0.0000
18.000	1.0000	1.0000	0.0000	1.0000
19.000	0.0000	1.0000	1.0000	0.0000
20.000	0.0000	1.0000	1.0000	0.0000
21.000	0.0000	0.0000	0.0000	1.0000
22.000	0.0000	0.0000	0.0000	1.0000
23.000	1.0000	1.0000	0.0000	0.0000
24.000	0.0000	0.0000	1.0000	1.0000
25.000	0.0000	1.0000	1.0000	0.0000
26.000	0.0000	0.0000	1.0000	0.0000
31.000	0.0000	0.0000	1.0000	0.0000
32.000	0.0000	0.0000	1.0000	1.0000
33.000	0.0000	1.0000	0.0000	1.0000
34.000	1.0000	1.0000	0.0000	1.0000
35.000	0.0000	0.0000	0.0000	0.0000
36.000	0.0000	0.0000	0.0000	1.0000
37.000	0.0000	0.0000	0.0000	0.0000
38.000	0.0000	1.0000	0.0000	0.0000
39.000	0.0000	0.0000	0.0000	1.0000
40.000	0.0000	0.0000	1.0000	0.0000
45.000	0.0000	1.0000	1.0000	0.0000
46.000	0.0000	1.0000	0.0000	1.0000
47.000	0.0000	1.0000	0.0000	0.0000
48.000	1.0000	0.0000	1.0000	0.0000
49.000	1.0000	0.0000	1.0000	0.0000
50.000	1.0000	1.0000	0.0000	0.0000
51.000	1.0000	0.0000	0.0000	0.0000
54.000	0.0000	0.0000	1.0000	0.0000
55.000	0.0000	0.0000	0.0000	0.0000
56.000	0.0000	0.0000	0.0000	0.0000
57.000	1.0000	1.0000	1.0000	0.0000
58.000	0.0000	0.0000	1.0000	0.0000
59.000	0.0000	1.0000	1.0000	0.0000
61.000	0.0000	0.0000	0.0000	1.0000
62.000	0.0000	1.0000	0.0000	0.0000
64.000	1.0000	1.0000	0.0000	1.0000
66.000	1.0000	0.0000	0.0000	1.0000
67.000	1.0000	1.0000	0.0000	0.0000
72.000	1.0000	0.0000	1.0000	0.0000
74.000	0.0000	0.0000	1.0000	0.0000
75.000	0.0000	1.0000	1.0000	0.0000

Site Number	Land Use	Beam Orient A	Field Orient	Beam Orient B
78.000	1.0000	1.0000	0.0000	1.0000
80.000	0.0000	0.0000	0.0000	1.0000
81.000	0.0000	1.0000	0.0000	1.0000
83.000	0.0000	1.0000	0.0000	0.0000
84.000	0.0000	0.0000	1.0000	0.0000
85.000	1.0000	1.0000	0.0000	0.0000
86.000	0.0000	0.0000	0.0000	0.0000
87.000	0.0000	1.0000	0.0000	0.0000
88.000	1.0000	0.0000	1.0000	0.0000

Coding for the indicator variables is as follows:

Land Use
If corn, LU = 1
If other than corn, LU = 0

Beam Orientation A
If far-nadir beam, BOA = 1
If near-nadir beam, BOA = 0

Field Orientation
If east-west, FO = 1
If north-south, FO = 0

Beam Orientation B
If west, BOB = 1
If east, BOB = 0

Appendix F: Compilation of All Weighted Data Set Variables

The values in Tables E-4 and E-5 of the basic set data are the same for the weighted set and are not repeated in this appendix.

Table F-1: Soil and Soil Moisture Values

Site Number	(0-5 cm) GSM	(5-10 cm) GSM	Percent Sand	Percent Clay	Bulk Density
1.0000	28.530	26.840	35.930	23.000	1.3000
2.0000	29.480	27.660	33.300	23.860	1.3150
3.0000	28.790	27.960	19.800	19.[illegible]10	1.3510
4.0000	19.400	19.810	27.100	29.100	1.3010
5.0000	25.690	27.640	33.800	26.600	1.2960
7.0000	30.220	35.680	26.650	13.960	1.0870
10.000	30.710	32.620	18.980	26.690	0.9540
15.000	43.670	39.400	42.700	20.600	1.4350
17.000	29.620	27.300	31.580	25.230	1.3400
18.000	29.180	26.130	28.800	22.200	1.2880
19.000	26.160	25.040	9.6000	29.250	1.2000
20.000	23.920	23.460	10.400	30.830	1.2350
21.000	34.550	34.830	25.400	30.250	1.2500
22.000	29.850	28.740	32.000	29.500	1.2000
23.000	30.960	30.700	30.600	20.600	1.3030
24.000	30.630	28.460	31.430	26.900	1.3270
25.000	28.000	27.730	32.000	27.100	1.2600
26.000	29.090	26.040	28.200	30.100	1.2500
31.000	29.960	26.550	38.900	22.900	1.3060
32.000	36.510	32.970	33.000	26.900	1.3880
33.000	25.730	25.880	34.400	22.670	1.3750
34.000	28.870	27.220	31.800	24.630	1.3700
35.000	38.050	32.820	26.000	30.000	1.2880
36.000	38.110	31.900	24.400	30.100	1.3120
37.000	33.930	33.080	31.000	24.000	1.2500
38.000	44.330	43.380	32.000	24.000	1.2500
39.000	31.040	32.340	31.860	28.640	1.2760
40.000	31.790	32.390	23.060	29.110	1.3670
45.000	25.810	29.100	32.000	30.200	1.3240
46.000	18.300	19.070	32.000	25.750	1.2540
47.000	27.530	26.800	22.600	30.280	1.3370
48.000	31.240	29.750	32.000	30.400	1.3580
49.000	33.520	31.160	30.800	29.650	1.2100
50.000	24.470	23.220	32.000	29.600	1.2180
51.000	29.420	29.670	32.000	29.900	1.2620
54.000	29.520	26.300	16.580	33.220	1.2830
55.000	26.570	27.000	27.800	28.800	1.2860
56.000	31.770	28.410	28.900	23.440	1.4120
57.000	31.120	29.490	28.400	29.810	1.2510

Table F-1: Compilation of All Weighted Data Set Variables (con't)

Site Number	(0-5 cm) GSM	(5-10 cm) GSM	Percent Sand	Percent Clay	Bulk Density
58.000	28.980	27.360	26.000	30.200	1.2520
59.000	24.450	26.120	27.500	28.080	1.3130
61.000	26.670	25.100	25.490	29.330	1.3270
62.000	36.670	36.010	27.930	26.040	1.3600
64.000	37.200	34.960	29.300	29.450	1.2590
66.000	33.660	32.760	21.200	30.700	1.3130
67.000	32.730	29.800	21.480	29.860	1.3170
72.000	28.320	26.650	21.170	30.590	1.2970
74.000	24.470	22.310	27.900	26.160	1.3740
75.000	36.530	35.210	20.000	32.080	1.2780
78.000	28.340	27.940	26.000	30.000	1.2880
80.000	30.030	28.210	31.600	28.090	1.2440
81.000	32.250	30.670	31.800	25.400	1.3230
83.000	39.450	36.750	23.000	30.860	1.2980
84.000	33.240	32.610	32.000	29.730	1.2410
85.000	34.720	34.740	20.000	31.000	1.3000
86.000	29.850	29.870	26.000	30.000	1.2880
87.000	42.950	32.960	23.600	30.200	1.3230
88.000	34.770	33.420	23.000	30.540	1.3350

Table F-2: Sensor Readings and Calculated Emissivity

Site Number	Footprint Time	Thermal Brightness	PRT5	Emissivity
1.0000	16:24:18.4	246.90	20.560	0.8406
2.0000	16:24:16.5	239.70	20.270	0.8169
3.0000	16:32:40.3	254.60	20.040	0.8684
4.0000	16:45:30.3	249.40	20.340	0.8498
5.0000	16:53:44.3	244.00	20.450	0.8311
7.0000	16:53:42.4	245.30	20.300	0.8359
10.000	17:35:32.8	240.60	17.900	0.8267
15.000	17:35:28.4	254.30	17.940	0.8736
17.000	17:35:20.5	257.60	17.030	0.8877
18.000	16:32:34.4	251.60	20.260	0.8575
19.000	16:24:22.4	235.40	20.160	0.8026
20.000	16:24:22.9	236.30	20.130	0.8057
21.000	16:24:26.8	252.10	20.100	0.8597
22.000	16:24:29.8	249.10	19.820	0.8503
23.000	16:32:33.4	248.90	20.880	0.8465
24.000	16:53:27.6	247.10	20.840	0.8405
25.000	16:53:27.6	253.90	20.830	0.8637
26.000	16:53:24.1	244.60	20.440	0.8331
31.000	16:53:16.2	236.20	20.870	0.8033
32.000	16:45:54.0	253.00	20.260	0.8623
33.000	16:45:52.0	242.90	21.440	0.8245
34.000	16:32:18.1	252.30	20.180	0.8601
35.000	16:24:46.5	251.00	20.600	0.8545
36.000	16:32:13.7	251.80	19.500	0.8604
37.000	16:32:13.2	245.80	19.500	0.8399
38.000	16:46:05.3	242.80	19.630	0.8293
39.000	17:06:23.1	241.00	18.330	0.8268
40.000	17:06:18.2	244.80	18.190	0.8403
45.000	16:46:14.2	240.20	20.500	0.8180
46.000	16:46:14.7	243.40	20.400	0.8292
47.000	16:25:02.8	245.00	21.090	0.8327
48.000	16:25:04.8	243.00	21.400	0.8250
49.000	16:25:06.2	240.20	21.400	0.8155
50.000	16:46:19.6	248.50	21.690	0.8428
51.000	16:52:57.0	244.30	20.470	0.8320
54.000	17:06:44.3	245.50	18.540	0.8416
55.000	16:52:52.1	246.90	21.280	0.8386
56.000	16:31:48.0	250.90	19.940	0.8561
57.000	16:31:34.2	234.60	19.870	0.8006
58.000	16:46:35.9	243.00	20.530	0.8274
59.000	16:46:35.4	242.30	21.140	0.8233
61.000	17:34:20.8	242.20	18.720	0.8298
62.000	17:34:23.3	249.10	18.180	0.8550
64.000	16:52:33.2	253.50	20.420	0.8635
66.000	16:52:27.4	253.80	20.500	0.8643
67.000	17:34:10.0	241.30	17.230	0.8310
72.000	17:34:06.1	261.00	17.600	0.8977
74.000	16:52:20.5	243.70	19.860	0.8317
75.000	17:34:02.1	251.30	17.780	0.8638

Table F-2: Sensor Readings and Calculated Emissivity (con't)

Site Number	Footprint Time	Thermal Brightness	PRT5	Emissivity
78.000	17:33:49.8	250.10	19.940	0.8533
80.000	16:52:11.6	229.80	20.590	0.7823
81.000	16:52:14.6	236.60	20.000	0.8071
83.000	16:31:08.1	234.10	19.370	0.8003
84.000	16:31:05.1	239.60	19.560	0.8186
85.000	16:31:02.6	240.10	19.780	0.8196
86.000	17:33:45.8	228.60	19.640	0.7808
87.000	17:33:43.9	233.40	19.380	0.7979
88.000	16:52:02.8	247.30	22.050	0.8377

Table F-3: Calculated Volumetric and Field Capacity Values

Site Number	(0-5 cm) VSM	(5-10 cm) VSM	(0-5 cm) FC	(5-10 cm) FC
1.0000	37.089	34.892	111.59	104.98
2.0000	38.766	36.373	113.12	106.13
3.0000	38.895	37.774	110.03	106.85
4.0000	25.239	25.773	65.870	67.262
5.0000	33.294	35.821	93.718	100.83
7.0000	32.849	38.784	106.48	125.72
10.000	29.297	31.119	75.161	79.835
15.000	62.666	56.539	205.61	185.50
17.000	39.691	36.582	112.27	103.48
18.000	37.584	33.655	109.01	97.620
19.000	31.392	30.048	74.008	70.840
20.000	29.541	28.973	68.664	67.343
21.000	43.187	43.537	109.94	110.83
22.000	35.820	34.488	95.801	92.239
23.000	40.341	40.002	121.28	120.26
24.000	40.646	37.766	112.22	104.27
25.000	35.280	34.940	97.485	96.545
26.000	36.362	32.550	94.291	84.405
31.000	39.128	34.674	120.38	106.68
32.000	50.676	45.762	141.32	127.61
33.000	35.379	35.585	105.85	106.47
34.000	39.552	37.291	113.00	106.54
35.000	49.008	42.272	125.60	108.33
36.000	50.000	41.853	126.78	106.12
37.000	42.412	41.350	121.63	118.58
38.000	55.412	54.225	159.97	156.54
39.000	39.607	41.266	107.07	111.55
40.000	43.457	44.277	110.71	112.80
45.000	34.172	38.528	90.547	102.09
46.000	22.948	23.914	64.616	67.334
47.000	36.808	35.832	92.153	89.709
48.000	42.424	40.400	112.11	106.77
49.000	40.559	37.704	107.47	99.901
50.000	29.804	28.282	79.606	75.539
51.000	37.128	37.444	98.771	99.610
54.000	37.874	33.743	88.498	78.845
55.000	34.169	34.722	89.904	91.359
56.000	44.859	40.115	127.90	114.38
57.000	38.931	36.892	101.45	96.140
58.000	36.283	34.255	92.748	87.563
59.000	32.103	34.296	85.120	90.933
61.000	35.391	33.308	91.209	85.839
62.000	49.871	48.974	136.27	133.82
64.000	46.835	44.015	123.29	115.87
66.000	44.196	43.014	109.19	106.28
67.000	43.105	39.247	107.79	98.142
72.000	36.731	34.565	90.860	85.502
74.000	33.622	30.654	91.705	83.610
75.000	46.685	44.998	112.66	108.59

Table F-3: Calculated Volumetric and Field Capacity Values (con't)

Site Number	(0-5 cm) VSM	(5-10 cm) VSM	(0-5 cm) FC	(5-10 cm) FC
78.000	36.502	35.987	93.547	92.226
80.000	37.357	35.093	101.58	95.422
81.000	42.667	40.576	120.58	114.67
83.000	51.206	47.701	127.57	118.84
84.000	41.251	40.469	109.99	107.90
85.000	45.136	45.162	110.36	110.42
86.000	38.447	38.473	98.531	98.597
87.000	56.823	43.606	143.23	109.92
88.000	46.418	44.616	116.10	111.60

Appendix G: Compilation of Scatter Plots of Individual Flight Lines

Included in this appendix are representative scatter plots of five of the six flight lines. Flight Line 5 is not included because it had but three sample locations. These representative figures are split between the weighted and unweighted values as well as thermal brightness/emissivity and gravimetric soil moisture/volumetric soil moisture/field capacity. The scatter plots were all very similar, so a variety of variables are shown to give an overall view of the data set.

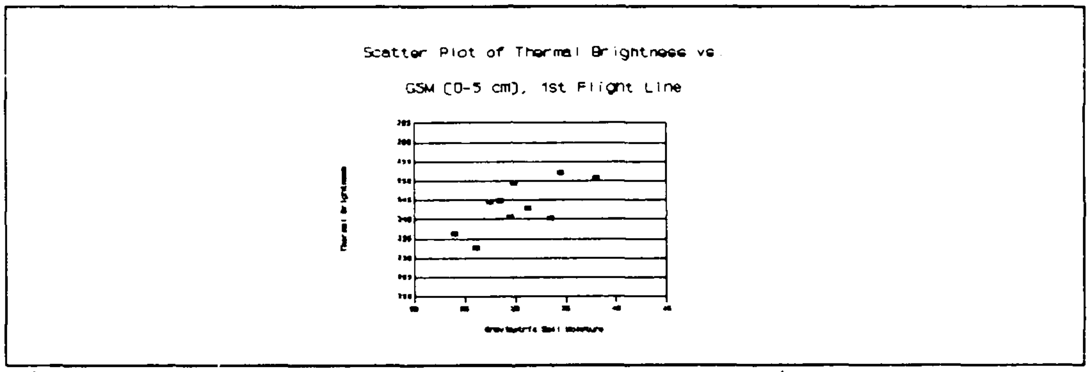

Figure G-1. Scatter Plot of Thermal Brightness vs. GSM (0-5 cm), 1st Flight Line

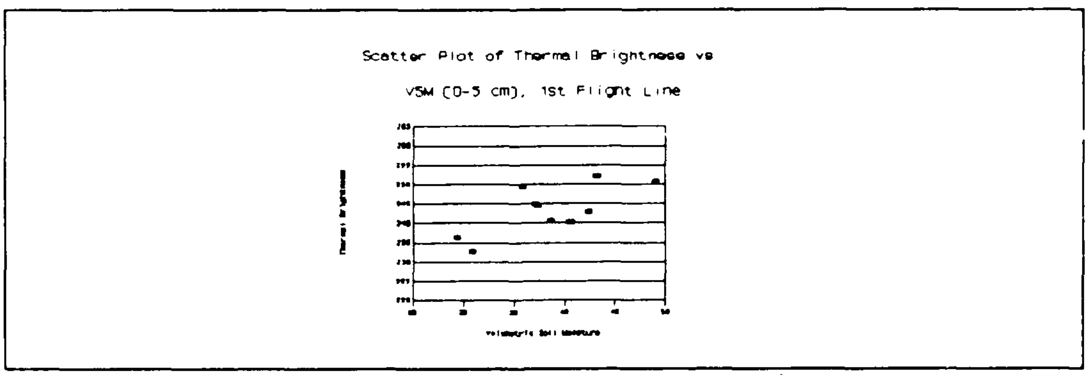

Figure G-2. Scatter Plot of Thermal Brightness vs. VSM (0-5 cm), 1st Flight Line

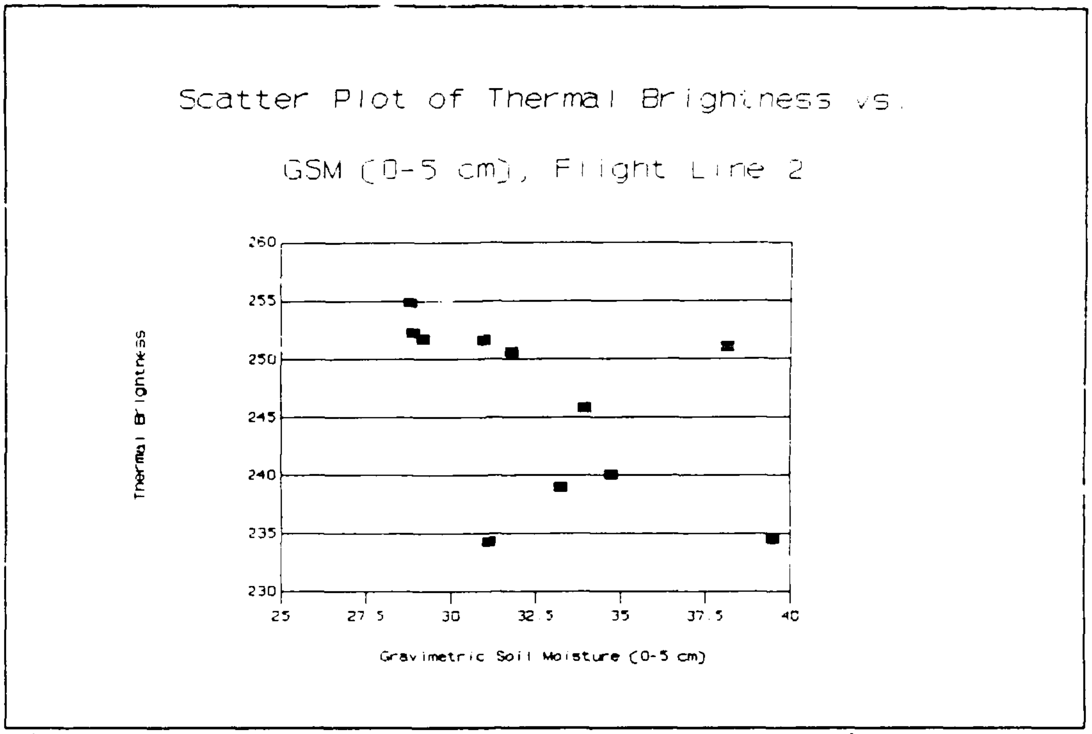

Figure G-3. Scatter Plot of Thermal Brightness vs. Gravimetric Soil Moisture (0-5 cm), Flight Line 2

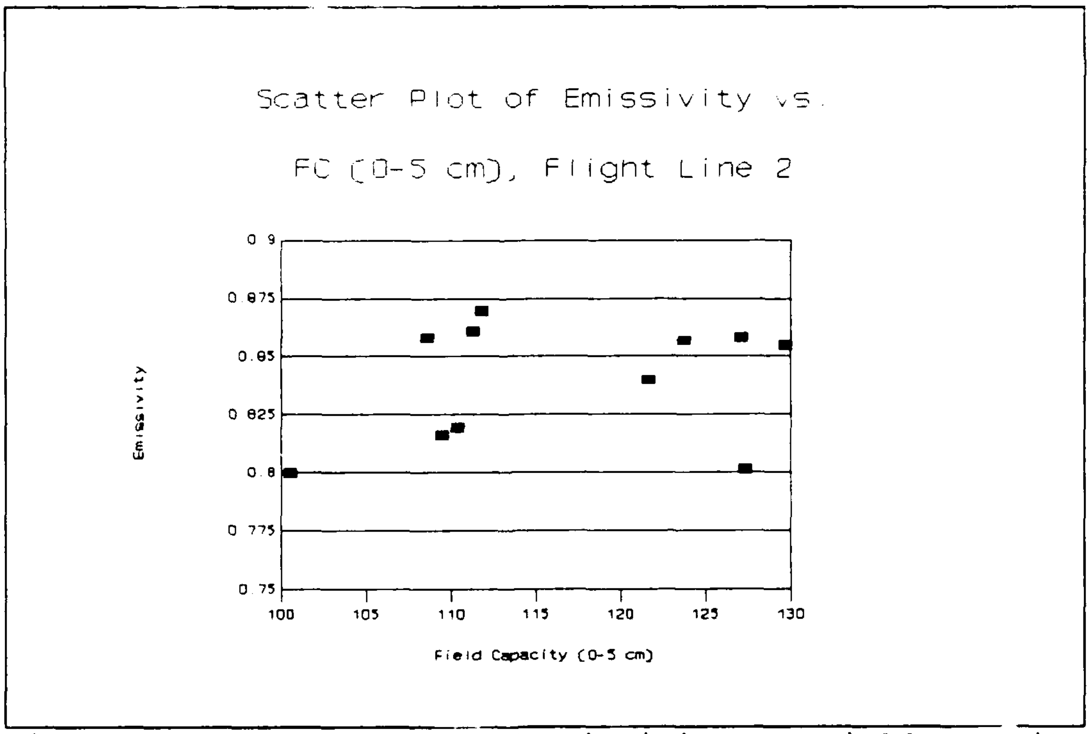

Figure G-4. Scatter Plot of Emissivity vs. Field Capacity (0-5 cm), Flight Line 2

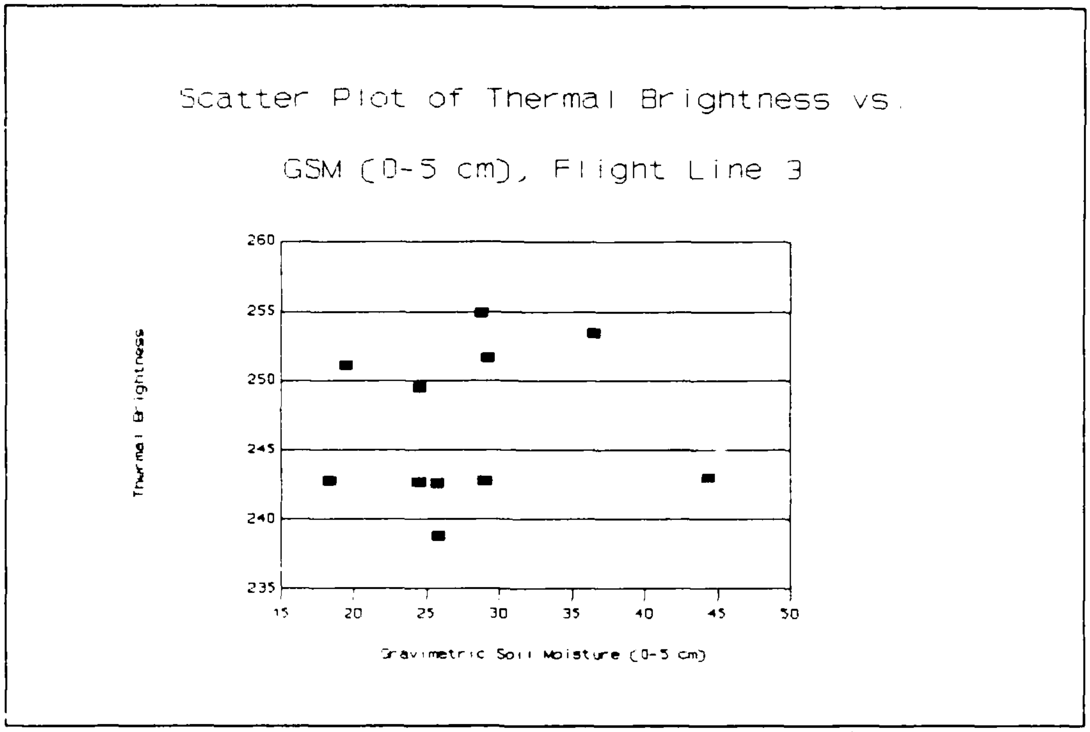

Figure G-5. Scatter Plot of Thermal Brightness vs. Gravimetric Soil Moisture (0-5 cm), Flight Line 3

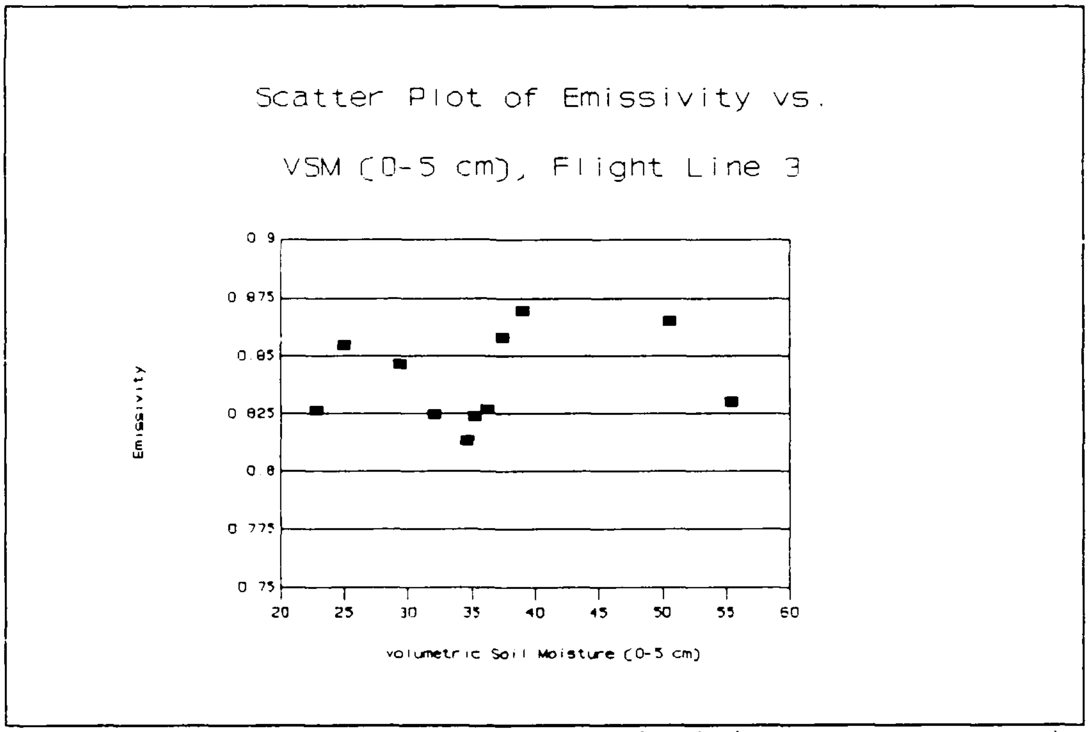

Figure G-6. Scatter Plot of Emissivity vs. Volumetric Soil Moisture (0-5 cm), Flight Line 3

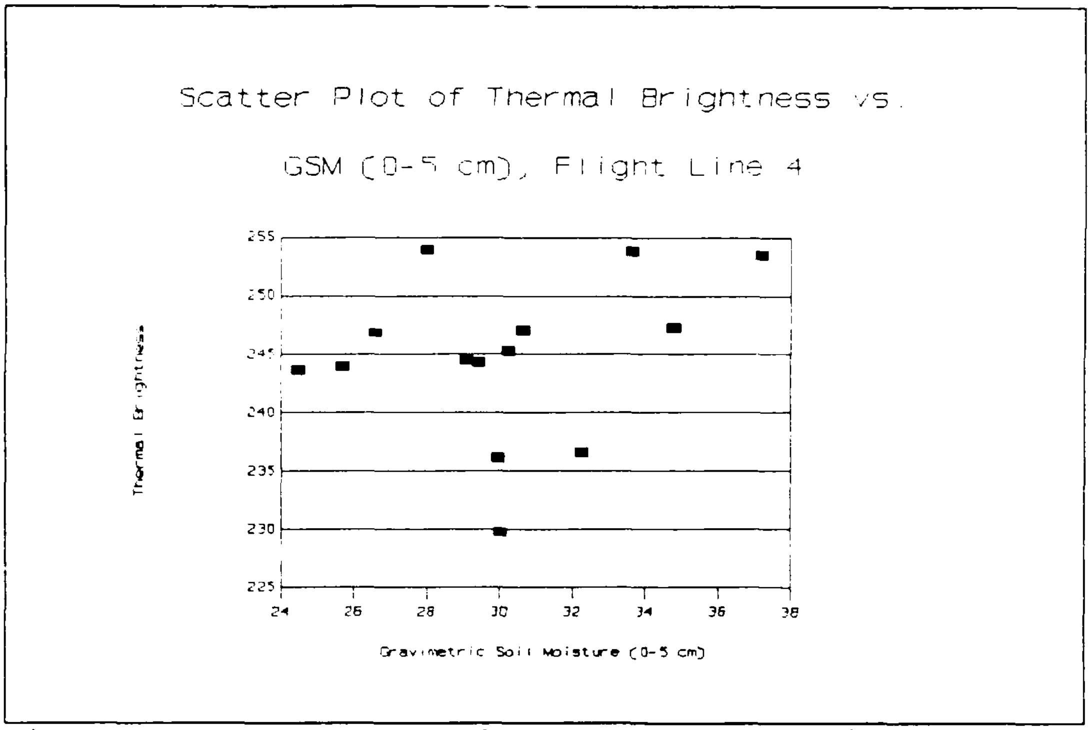

Figure G-7. Scatter Plot of Thermal Brightness vs. Gravimetric Soil Moisture (0-5 cm), Flight Line 4

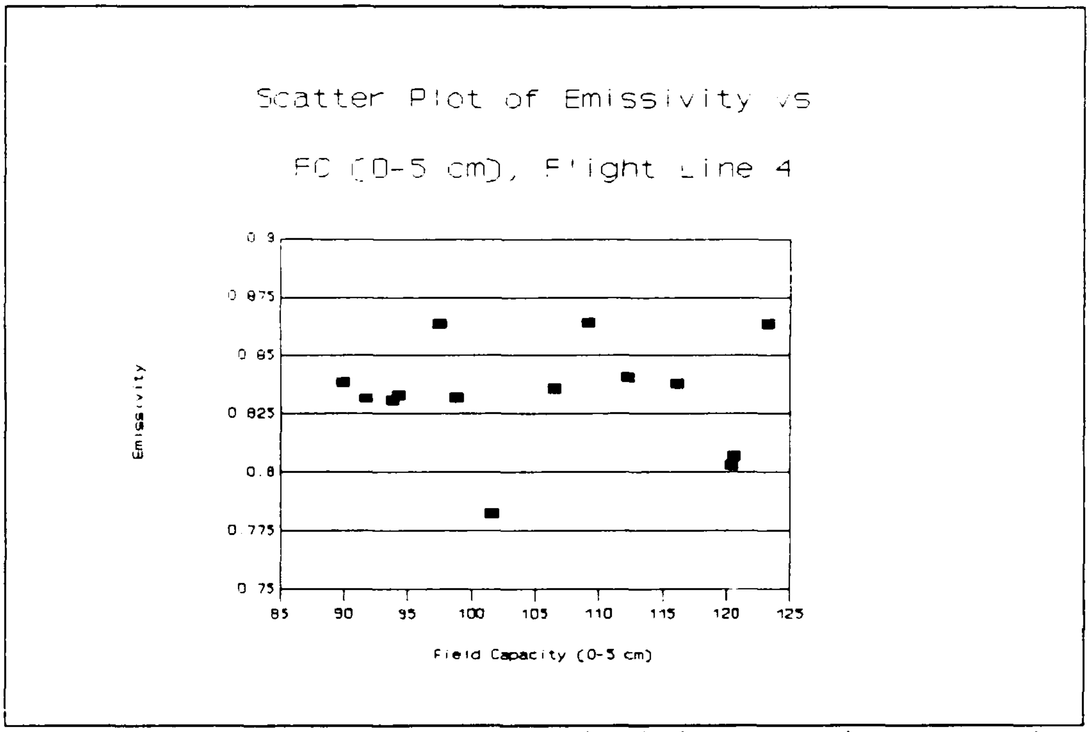

Figure G-8. Scatter Plot of Emissivity vs. Field Capacity (0-5 cm), Flight Line 4

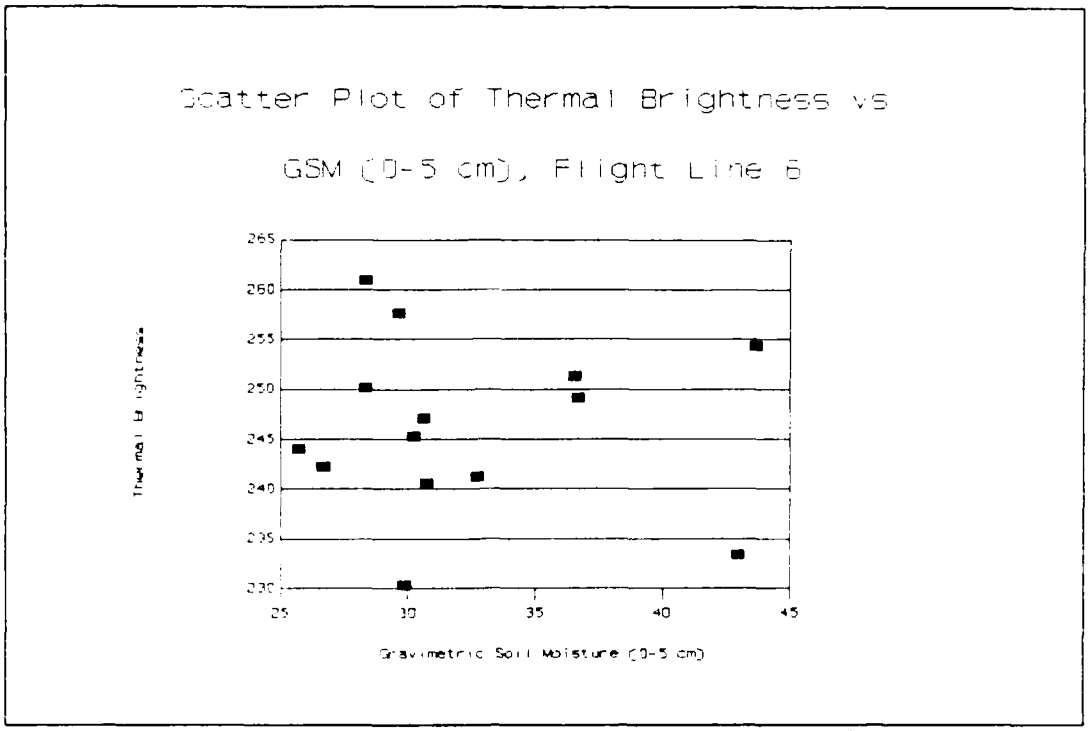

Figure G-9. Scatter Plot of Thermal Brightness vs. Gravimetric Soil Moisture (0-5 cm), Flight Line 6

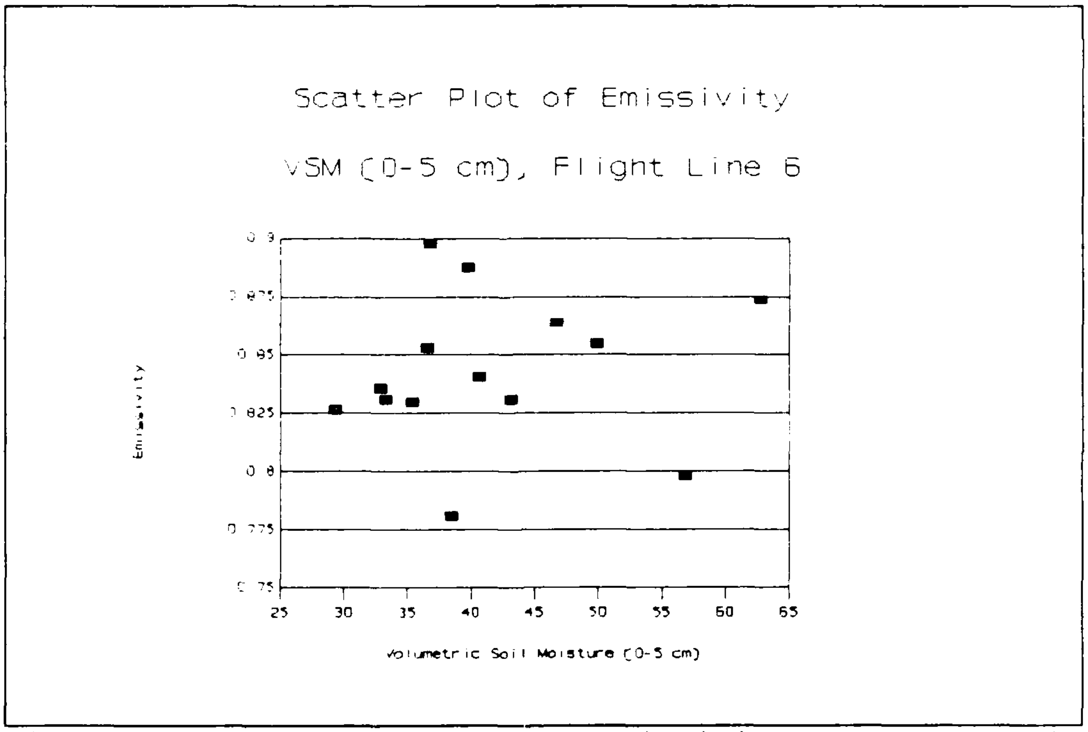

Figure G-10. Scatter Plot of Emissivity vs. Volumetric Soil Moisture (0-5 cm), Flight Line 6

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Vita

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The purpose of this thesis was to analyze a collection of passive microwave sensor output and determine if a relationship existed between that output and soil moisture content. It was also the objective of this thesis to identify procedural errors which may have hindered the thorough analysis of the data set and propose potential solutions.

In processing the data into a form which could be analyzed, a weighting technique was developed to help reduce the variability in the sensor readings caused by the large footprint size. This weighting technique used a Bessel function to represent the decrease in beam strength within a footprint. Multiple footprints containing the same sample ground location were then weighted based on the ground sample position in the footprint.

The study failed to show that any relationship exists between soil moisture and passive microwave response. The results, rather than being significant, are inconclusive. Many procedural and processing errors in the experiment, coupled with a lack of data on some important variables, left the analysis with only a small chance of success. However, these errors are identified and potential solutions for many of these errors are identified.

The weighting technique showed a statistically insignificant increase in the relationship values, yet with additional study could prove to be an asset in this field.